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Nucleate Pool Boiling of R-114/Oil Mixtures in a Small Enhanced Tube Bundle

by

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

ABSTRACT

Heat transfer tests were carried out using a small tube bundle of Turbo-B tubes in a pool of different R-114/oil mixtures. By accurately instrumenting five tubes within the bundle, both the convective and nucleate boiling regions were studied in detail, with emphasis on the 'bundle effect' (ie. the effect of the lower tubes in operation on the upper tubes within the bundle). In addition, the influence of increased amounts of oil on the tube bundle was studied to see how this affected the overall heat transfer and in particular, the shape of the hysteresis loop.

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NOMENCLATURE

SYMBOL	UNITS	NAME/DESCRIPTION
Aas	V	Voltage output from current sensor
A_c	m^2	Tube-wall cross sectional area
A_s	m^2	Area of heated surface
C_p	J/kg K	Specific heat
D_i	m	Inside tube diameter
D_o	m	Outside tube diameter
D_{tc}	m	Thermocouple location diameter
fpi		Fins per inch
g	m/s^2	Gravitational acceleration
h	W/m^2 K	Heat transfer coefficient of enhanced tube surface
h_b	W/m^2 K	Heat transfer coefficient of tubes unheated ends
ht	m	Height of liquid column above a instrumented tube
k	W/m K	Thermal conductivity of refrigerant
k_{cu}	W/m K	Thermal conductivity of copper
L	m	Heated length of the tube
L_u	m	Unheated length of the tube
L_c	m	Corrected unheated length of the tube
n	1/m	Parameter in calculation of q_f
Pr		Prandtl number
p	m	Perimeter of the tube outside surface
ΔP	Pa	Hydrostatic pressure difference between tube and liquid free surface

q	W	Heat transfer rate
q''	W/m^2	Heat flux
q_f	W	Heat transfer rate from unheated smooth tube ends
t	m	Thickness of the tube wall
T	C	Temperature
T_{film}	C	$(Tsat_c + \overline{T}wo) / 2$, Film temperature
T_{filmK}	K	Film thermodynamic temperature
Tld1	C	Liquid temperature reading from T(3)
Tld2	C	Liquid temperature reading from T(4)
Tsat	C	Saturation temperature
$Tsat_c$	C	Corrected saturation temperature due to hydrostatic pressure difference
$\overline{T}wi$	C	Average inside wall temperature
$\overline{T}wi\text{-}K$	K	Average inside wall thermodynamic temperature
$\overline{T}wo$	C	Average outside wall temperature
Vas	V	Voltage output from voltage sensor
α	m^2/s	Thermal diffusivity
β	1/K	Thermal expansion coefficient
μ	kg/m s	Dynamic viscosity of liquid
ν	m^2/s	Kinematic viscosity of liquid
ρ	kg/m^3	Density of liquid
Φ	C	Fourier conduction term
θ_b	C	$\overline{T}wo - Tsat_c$, Wall Superheat

I. INTRODUCTION

A. BACKGROUND

One of today's major environmental concerns is the depletion of the earth's protective ozone layer. In 1987, an international conference was held in Montreal, Canada to address the problems caused by Chlorofluorocarbons (CFCs) to the earth's ozone layer. CFCs are manmade chemicals of chlorine, fluorine, and carbon and are unique in that they have a combination of desirable properties: low in toxicity, non-flammable, non-corrosive, non-explosive, extremely stable and compatible with many other materials. This extreme stability is what causes problems to the ozone layer due to the fact that CFCs only break down in the upper atmosphere when subjected to intense ultraviolet radiation. This break down produces chlorine which has been linked to the depletion of the earth's ozone layer.

In September 1987, 24 nations representing the United Nations Environment Program (UNEP) met and signed the Montreal Protocol. They discussed the substances that deplete the ozone layer [Ref.1] and called for a near-term freeze on the production and consumption of these substances. The agreement required production of these chemicals to be cut back to 1986 levels followed by a two-phased reduction culminating in cutbacks of 50% by mid-1998; this came into effect on July 1, 1989. In 1990, a progress meeting was held in London where UNEP delegates agreed to completely phase out all CFCs by the year 2000 [Ref. 2]. In the spring of

1992, President Bush pushed up the complete phase out od CFC's by the year 1995.

The U.S. Navy uses a number of different CFCs (designated by "R" for refigerants) for various refrigeration and air conditioning (AC) needs. Presently, the U.S. Navy has approximately 1850 shipboard AC plants using both R-12 (in reciprocating compressor) and R-114 (in centrifugal compressor) plants. To comply with the Montreal Protocol and U.S. legislation, the Mechanical Systems Branch (Code 2772) at the Naval Surface Warfare Center (NSWC) is pursuing research in the elimination of shipboard use of CFCs. As mentioned by Chilman [Ref. 3] this research is to be completed in three phases:

1. To identify in the short term suitable alternative ozone-safe chemicals to replace R-114 and R-12. To accomplish this task, the heat transfer characteristics must be similar to the existing refrigerants in place and hence the need for a database exists for current refrigerants (R-114 and R-12) so that they can be compared to the new proposed refrigerants (HFC-124 and HFC-134A respectively).

2. In the longer term, to research, develop, and test substitute chemicals and alternative technologies to replace existing CFC uses.

3. To implement new cooling system technologies into the fleet which do not depend on CFCs or their replacement.

This thesis is a continuation of the previous work at NPS and supplements NSWC's research on alternatives to CFCs by establishing baseline nucleate pool boiling data of pure R-114 and R-114/oil mixtures from a small bundle of enhanced tubes representing a section of a flooded evaporator. Emphasis is placed on the natural convection and boiling

regions, hystersis phenomena, and analysis of various oil concentrations on the overall heat transfer performance.

B. OBJECTIVES

The objectives of this thesis are as follows:

1. Understand in greater detail both the convection and nucleate pool boiling phenomena and hysteresis effects within a small Turbo-B tube bundle.

2. Obtain data using a Turbo-B tube bundle for increasing and decreasing heat flux for R-114/oil mixture with oil concentrations of 0, 1, 2, 3, 6, and 10 percent.

3. Compare data with earlier studies at the Naval Postgraduate School using R-114/oil mixtures for other enhanced tube surfaces.

II. LITERATURE SURVEY

A. SMOOTH TUBE BUNDLES

In recent years significant progress has been made in understanding nucleate boiling heat transfer phenomena on the shell side of flooded evaporators. Extensive work on smooth tube bundles has been reported by Cornwell (Leong and Cornwell [Ref. 4], Cornwell et al. [Ref. 5], Cornwell and Scoones [Ref. 6], Cornwell [Ref. 7]). Cornwell and Schuller [Ref. 8] conducted a photographic study of boiling R-113 in a smooth tube bundle at one atmosphere. One of their conclusions was that bubbles leaving the lower tubes in the bundle impacted and caused a sliding motion around the upper tubes. Cornwell and Schuller observed the two-phase flow patterns and deduced that sliding bubbles from lower tubes on upper tubes could account for significant heat transfer in the top part of the bundle. Cornwell [Ref. 7] later found that in the nucleate boiling region, sliding bubbles and liquid forced convection could account for all the heat transfer in the top of the bundle.

The influence of tube position within a bundle of smooth tubes using R-11, R-12, R-22 and R-113 has been studied extensively by Wallner [Ref. 8], Fujita et al. [Ref. 9], Chan and Shourki [Ref. 10], Rebrov et al. [Ref. 11], and Marto and Anderson [Ref. 12]. Using both in-line and staggered tube arrangements with various tube pitch-to-diameter ratios between 1.2 and 2.0, their work verified that the influence of the lower tubes in a bundle can significantly increase the heat transfer performance

of upper tubes at low heat fluxes due to two-phase convective effects. At high heat fluxes (typically > 50 kW/m^2) in the fully developed nucleate boiling region, the data for all the tubes merged onto a single curve. This is representative of a single smooth tube and shows that there is no 'bundle effect' (ie. no improvement over a single tube under similar conditions) in the high heat flux (nucleate boiling) region.

Chan and Shoukri [Ref. 10] studied the boiling characteristics of a smooth in-line tube bundle in R-113. They concluded that at lower heat fluxes, the heat transfer process is strongly influenced by two-phase convection effects, resulting in higher heat transfer coefficients on the upper tubes. At high heat fluxes, however, they found that the dominant mode of heat transfer was nucleate boiling from the upper tubes and that convective effects from below were insignificant. At these high fluxes, the bundle performance was similar to the trends of a single tube in a single tube apparatus. Fujita et al. [Ref. 9] also found that the heat transfer at low heat fluxes using a smooth tube bundle in R-113 was enhanced by convection induced by rising bubbles (ie. a steady increase in performance of the upper tubes as additional lower tubes were activated). They attributed this enhancement to the "positive bundle effect". A high heat fluxes, this enhancement disappeared.

Anderson [Ref. 13] found similar effects as above for a smooth tube bundle in pure R-114. Furthermore, he reported that the presence of up to 3% oil (by mass) actually improved the heat transfer performance. This is similar to data reported for a single smooth tube by Wanniarachchi et al. [Ref. 14]. Furthermore, at an oil concentration of 10%, only a slight degradation in the heat transfer (compared to pure R-114) was found. He

obtained a maximum heat transfer performance for the bundle at an oil concentration of 2%.

B. ENHANCED TUBE BUNDLES

Much less work has been done on enhanced tubes (Enhanced means any surface that is not smooth). However, the effects at high and low heat fluxes mentioned above are similar to those obtained for finned tube bundles by Yilmaz and Palen [Ref. 15], Muller [Ref. 16], and Hahne and Muller [Ref. 17]. Stephen and Mitrovic [Ref. 18] looked at R-12 and R-114 boiling from a GEWA-T tube bundle. Apart from the magnitude of the heat transfer coefficient varying with fluid, the trends are very similar to those mentioned above for smooth and finned tube bundles.

For porous coated surfaces, Czikk et al. [Ref. 19] found no 'bundle effect' over a wide range of heat flux (1-100 kW/m^2) and the bundle data agreed closely with single tube data. Arai et al. [Ref. 20] found that the 'bundle effect' for a Thermoexcel tube bundle was smaller than that found for a smooth or finned tube bundle. However as before, any 'bundle effect' was eliminated at high heat fluxes where the data for all the tubes agreed closely with single Thermoexcel tube results. These effects are similar to those found by Czikk et al. [Ref. 19] for the porous coated.

Chilman [Ref. 3] reported experiments with a Turbo-B tube bundle in pure R-113, conducting both increasing and decreasing heat flux tests. He concluded that in the natural convection region, heated lower tubes do not have any influence on the heat transfer from upper tubes. Also, Chilman

reported the presence of heated lower tubes within a bundle reduced the incipient boiling point.

Stephan and Mitrovic [Ref. 18] reported the influence of oil on the boiling heat-transfer coefficient of R-12 using a T-shaped finned tube (Gewa-T) bundle. They reported that the ratio of oil to no oil heat-transfer coefficients decreased with the mass fraction of oil for all except the highest heat flux (22 kW/m^2) where an increase in heat transfer was noted for oil concentrations between 1 and 6% . They concluded that the influence of oil on heat transfer was mainly due to the thermal properties of the specific oil used in the experiments and its interaction with the refrigerant.

Schlager et al. [Ref. 21] summarized the influence of oil on refrigerant in pool boiling. They stated that under certain conditions (typically low pressure and high heat flux), the heat transfer coefficient <u>increased</u> at low oil concentration. Stephan [Ref. 22] first pointed this out and attributed the phenomenon to foaming. Burkhardt and Hahne [Ref. 23] for a finned tube bundle found that the maximum heat transfer coefficient, which was 10% to 15% above the oil-free value, occurred at a concentration of about 4%.

Heimbach [Ref. 24] conducted experiments with R-12/oil mixtures on a finned tube bundle. He reported that the presence of up to 2% oil, did not affect the heat transfer performance significantly. However at higher concentrations (3% to 7%), an increase in the heat transfer was observed. He also attributed this to foaming and postulated that changes in the properties of the mixture might facilitate the formation of bubbles.

Anderson [Ref. 13] and Akcasayar [Ref. 25] conducted experiments with finned (19 fpi) and High Flux (porous coated) tube bundles in pure R-114 and R-114/oil mixtures in the same apparatus. Anderson reported a maximum heat transfer performance at an oil concentration of 3% for the finned tube bundle. Akcasayar also reported that the finned tube bundle performance increased 1.65 times with 3% oil concentration (compared with pure R-114) at the maximum heat flux level. For 6% and 10% oil concentrations, the performance of the bundle, when compared with lower oil concentrations, decreased. This was especially significant at a 10% oil concentration. Compared with the finned tube bundle, the High Flux tube bundle had a 1.5 times better heat transfer performance at a heat flux of 30 kW/m^2 in pure R-114. However, these performance ratios decreased with increased oil concentrations such that the finned bundle outperformed the High Flux bundle at 6% oil concentration. This was especially true at the highest heat fluxes where the High Flux bundle performance was not much better than a smooth tube bundle of similar size.

III. EXPERIMENTAL APPARATUS

A. TEST APPARATUS OVERVIEW

The experimental apparatus including the auxiliary equipment and the evaporator/condenser is shown in Figure 1. The following is only a general description of the whole experimental apparatus. A more detailed look at the condenser and evaporator is provided in section C. Further information about the apparatus is provided by Murphy [Ref. 26] and Anderson [Ref. 13].

The experimental apparatus is essentially made up of three closed loops. The first loop consists of an 8 ton refrigeration unit located outside the laboratory which is used to cool an ethylene glycol/water mixture. The second loop is the ethylene glycol/water mixture flowing through the condenser. This mixture is contained within a large sump within the laboratory. The flow rate through the condenser is delivered by two pumps which can be operated independently or together; this coolant mixture condenses the refrigerant vapor in the condenser and maintains system pressure and temperature. Pump number one provides coolant flow through the four test condenser tubes as well as to one of the auxiliary condenser coils (bottom coil). Pump number two provides coolant through a manifold which distributes the coolant to the remaining four auxiliary condenser coils within the condenser. The third loop is the evaporator and condenser itself designed for reflux operation. The vapor generated

in the evaporator flows upward and condenses in the condenser; the condensate then returns to the evaporator via gravity.

B. AUXILIARY EQUIPMENT

1. 28 kW Refrigeration Unit

This unit was used to cool a 1.8 m^3 reservoir sump of an ethylene glycol/water mixture (coolant) to the desired temperature needed to condense the refrigerant vapor. For R-114, the temperature control was set to maintain the sump at -15 °C. The refrigeration unit had a cooling capacity of 28 kW (8 tons).

2. Ethylene Glycol/Water Mixture

The coolant used was a 54% (by weight) ethylene glycol/water mixture. This refrigerated mixture was used to control the system pressure and temperature by circulating coolant through the auxiliary condenser coils and/or condenser test tubes at different flow rates.

3. Pumps

Two pumps were available to circulate the coolant from the sump through the condenser. Pump number one fed four test condenser tubes and one of the auxiliary condenser coils. Pump number two fed the other four auxiliary condenser coils. Pump number one was the primary pump used at low heat fluxes; pump number two was started (as necessary) at high heat fluxes to maintain the desired saturation pressure in the evaporator.

4. Flowmeters

Five calibrated float-type flowmeters, connected to pump number one, were used to measure the flow rates passing through the four test condenser tubes and one auxiliary condenser coil. One additional

flowmeter (connected to pump number two) was used to measure the total flow to the remaining four auxiliary condenser coils. Each of the five auxiliary condenser coils had a globe valve to regulate (or shut off) flow as desired. For the four test condenser tubes, the coolant flow was regulated by a flowmeter valve.

C. EVAPORATOR/CONDENSER

An overall view of the evaporator and condenser is shown in Figure 2. The evaporator was designed to simulate a small portion of a refrigerant flooded evaporator. Front and side views of the evaporator are shown in Figures 3 and 4. It was fabricated from stainless steel plate and formed into a short cylinder, 610 mm in diameter and 241 mm long. Electrically-heated tubes were cantilever-mounted from the back wall of the evaporator to permit viewing along the axis of the tubes through the lower of two viewing windows. A plexiglas plate was attached to the front of the tube bundle to ensure tube alignment during experiments. Each viewing window had a layer of glass and plexiglas, the glass being used on the refrigerant side in order to prevent surface cracking of the plexiglas. The plexiglas gave the glass added strength and served as a safety barrier in case the glass broke during pressurization.

The electric power can be applied separately to each set of heaters using a STACO 240 V, 23.5 kVA rheostat controller shown in Figure 5. Also, the desired number of instrumented tubes, active tubes, simulation or auxiliary heaters can be individually activated by using circuit breakers. The five simulation heaters, each with a maximum rating of 4 kW, were mounted below the test bundle in order to simulate 15 additional

tube rows in a larger bundle and to provide an inlet vapor quality into the bottom of the test bundle as suggested by Webb [Ref. 27]. The liquid pool was maintained at 2.2 °C (corresponding to a saturation pressure of 1 atmosphere) by passing coolant through the condenser.

Figure 6 is a schematic sectional view of the evaporator that shows the four kinds of heated tubes installed in the evaporator. These were instrumented, active, auxiliary, and simulation. For this study only the instrumented, active, and simulation heaters were used; the auxiliary heaters are needed for experiments either at higher pressures or for other refrigerants which have a higher normal boiling point (such as R-113). Table 1 gives the power rating for these heaters and the number used in the evaporator.

The tube bundle itself consists of instrumented, active, and dummy tubes. The location of each tube is represented by the respective letter I, A, and D as shown in Figure 6. The test bundle consists of two types of heated tubes: 12 active tubes (marked "A") which contained 1 kW cartridge heaters, and 5 instrumented tubes (marked "I") which, in addition to the 1 kW cartridge heaters, contained six wall thermocouples each.

In measuring boiling heat transfer coefficients, great care must be exercised with the cartridge heater and temperature measuring instrumentation to ensure good accuracy. The instrumented test tubes were fabricated using the same method as that used by Hahne and Muller [Ref. 17] and Wanniarachchi et al. [Ref. 14]. The exact procedure can be found in Eraydin [Ref. 28]. Figure 7 is a cross-sectional sketch of an instrumented tube, showing the construction details and the location of the wall thermocouples. The thermocouples were embedded in the wall at

different circumferential and longitudinal positions along the heated section of the tube shown in Figure 7.

The five instrumented tubes were located along the centerline of the tube bundle, forming a vertical in-line column. All the instrumented and active tubes were Turbo-B tubes made by Wolverine Tube Co. (see Section E). These tubes were nominally 15.9 mm in outside diameter and were arranged in an equilateral triangular pitch (ie. centerline-to-centerline spacing) of 19.1 mm, giving a pitch-to-diameter ratio of 1.35. The thickness of the Turbo-B enhancement was 0.85 mm giving a diameter to the base of the enhancement of 14.2 mm.

The bundle also contained a number of unheated dummy smooth tubes (marked "D") that were used to guide the two phase mixture through the bundle. The dummy tubes were made from commercially available 15.9 mm OD smooth copper tubing. Two vertical baffle plates made of aluminum were used on either side of the bundle to restrict circulation into and out of the bundle at the sides. A dummy rack (Figure 8) consisting of 12 solid rods made of aluminum (15.9 mm OD and spaced 19.1 mm from centerline-to-centerline) was placed below the tube bundle. This rack had a triangular pitch arrangement with vapor retaining plates on the sides and was designed for two purposes: to collect all rising two phase flow generated by the simulation heaters and direct it into the test bundle and to simulate vapor passing through a large bundle before reaching the instrumented tubes. A small open space (approximately 5 mm in height) was left between the bundle and dummy tube rack. This space allowed some refrigerant from below to enter the bundle and replace the vapor being generated in the bundle. However, there was also a space below the dummy

rack that allowed the majority of the circulation to occur. Thus, liquid/vapor circulation was vertically upward over the five instrumented test tubes with no net horizontal component. Most of the liquid-vapor mixture after passing through the bundle was separated when it reached the pool surface. However, due to the strong circulation patterns set up within the liquid pool, some vapor bubbles remained trapped in the liquid and circulated around the pool.

The condenser included four test tubes (each 1.219 m in length and 15.9 mm OD) in a vertical in-line column and five auxiliary copper coils. For the boiling experiments, these tubes were used to regulate the pressure and temperature in the evaporator. The condenser was designed to permit independent condensation studies of small in-line tube bundles, using the evaporator as a source of vapor. Details of the condenser can be found in Mazzone [Ref. 29].

D. DATA ACQUISITION SYSTEM/INSTRUMENTATION

As described by Akcasayar [Ref. 25], a Hewlett Packard HP-3497A Data Acquisition System, HP-9125 computer and HP-701 printer were used for data acquisition, data reduction and data printing respectively. Although an HP-9826 computer and HP-7470A plotter can be used for final graph printing, a Macintosh computer (using Criketgraph) was utilized. As described by Anderson [Ref. 13], type-T copper-constantan thermocouples were used to make temperature measurements on the HP-3497A using a relay multiplexer assembly equipped with thermocouple compensation. A 20-channel relay multiplexer card was used to measure the voltage output from both the voltage and current sensors. The voltage measurements were taken

from separate sensors that measured the voltage going to the tube bundle, the simulation heaters and the auxiliary heaters. The total current going through the auxiliary and simulation heaters was measured using an American Aerospace Control (ACC) current sensor. The current to each instrumented tube heater was measured using five identical current sensors. The voltage supplied to the other active tubes was also measured, but the current of each active tube was not. Instead, the total current for a pair of active tubes was measured, and this was sufficient since these tubes each had the same power output (1000 W) as the instrumented test tube heaters and there was no apparent reason to monitor each active tube individually. Computer channel assignments for data acquisition and array assignments are given in Table 2.

E. GEOMETRY OF TURBO-B TUBE

The Turbo-B tube, manufactured by Wolverine Tube Inc., contained an enhanced surface geometry. The exterior boiling enhancement is made by raising low integral fins, cutting diagonally across these fins, and then rolling the fins to compress them to form mushroom-like pedestals [Ref. 30]. This process forms numerous re-entrant passageways. Figure 9 shows the surface of the tube at 25 times its actual size. The tube is currently available in copper, cupro-nickel, and low carbon steel.

The relative dimensions of the tube used in this study are as follows:

Tube material - Copper

Nominal Outside diameter = 15.9 mm

Enhanced surface length = 203.2 mm

Thickness of Enhancement = 0.85 mm

Diameter to Base of Enhancement = 14.2 mm

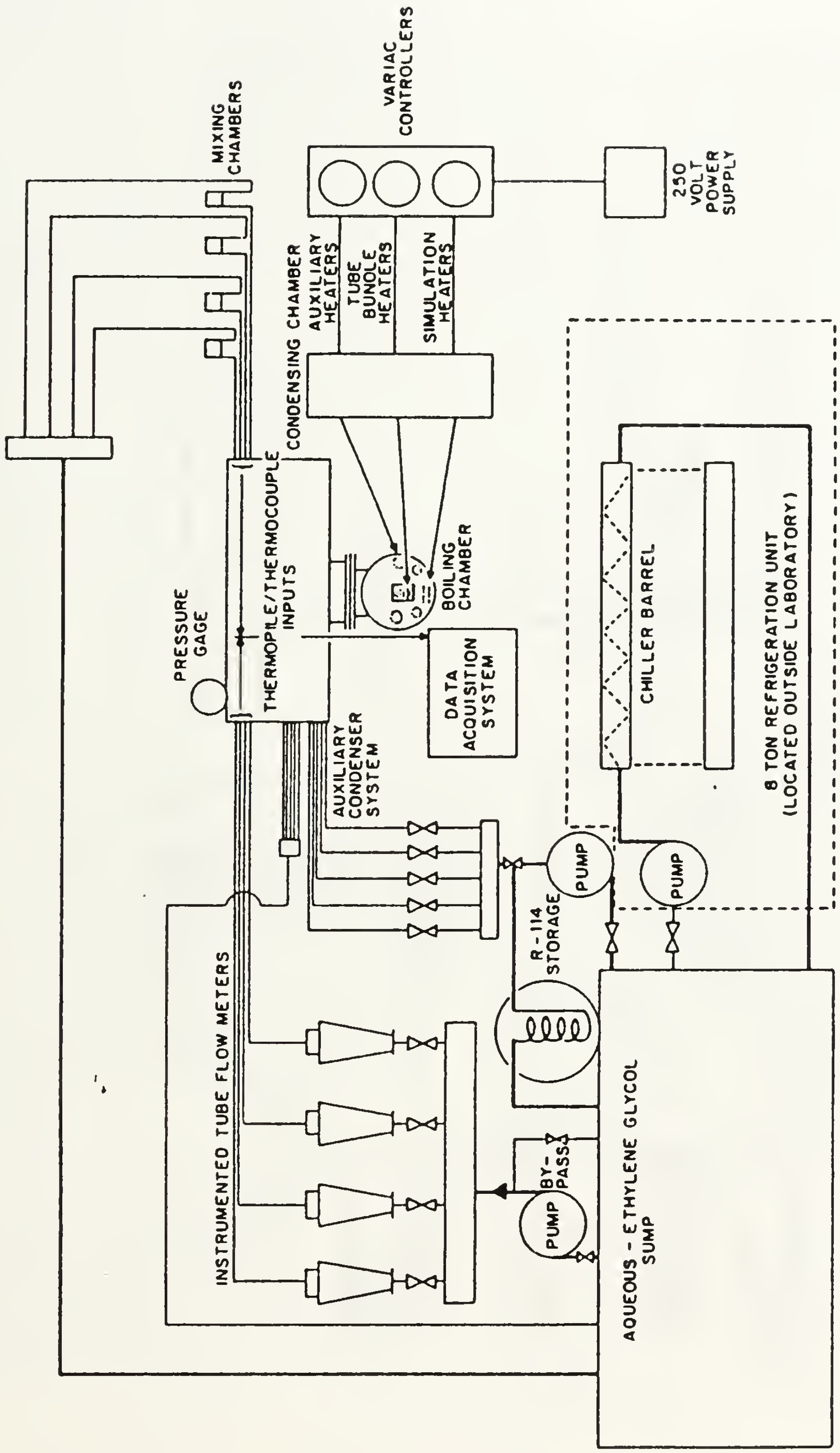

Figure 1. Schematic View of the Experimental Apparatus

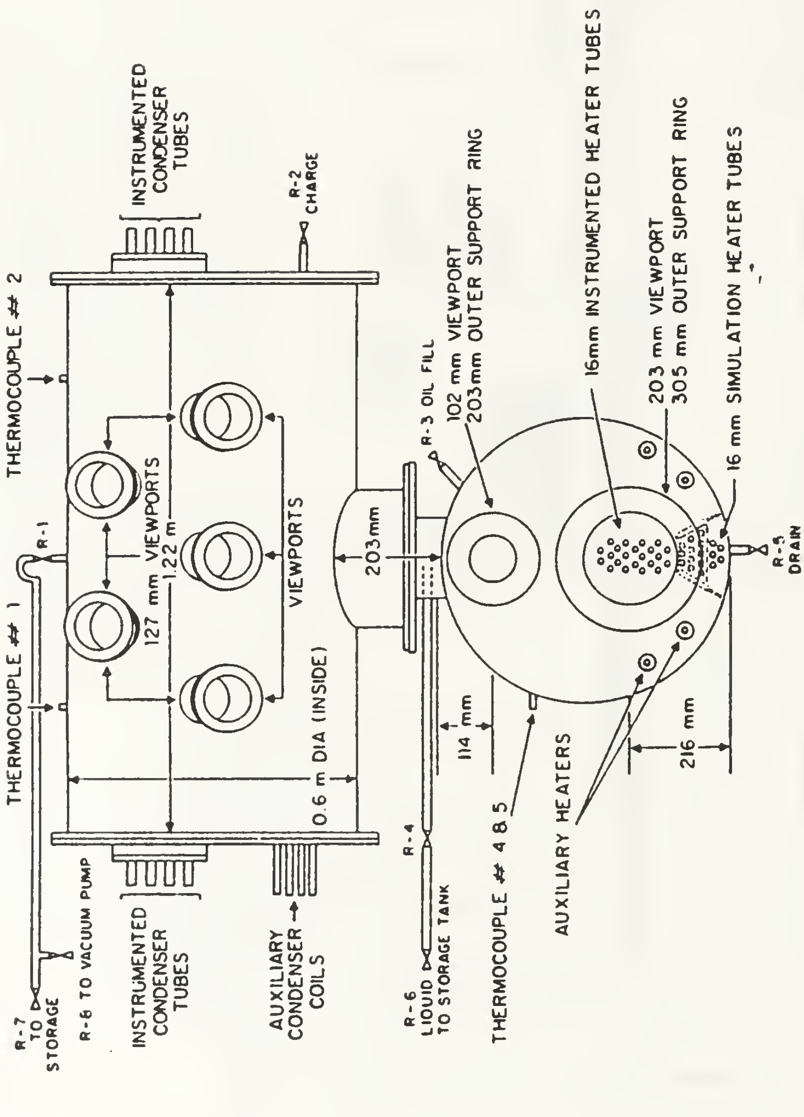

Figure 2. Evaporator/Condenser Schematic

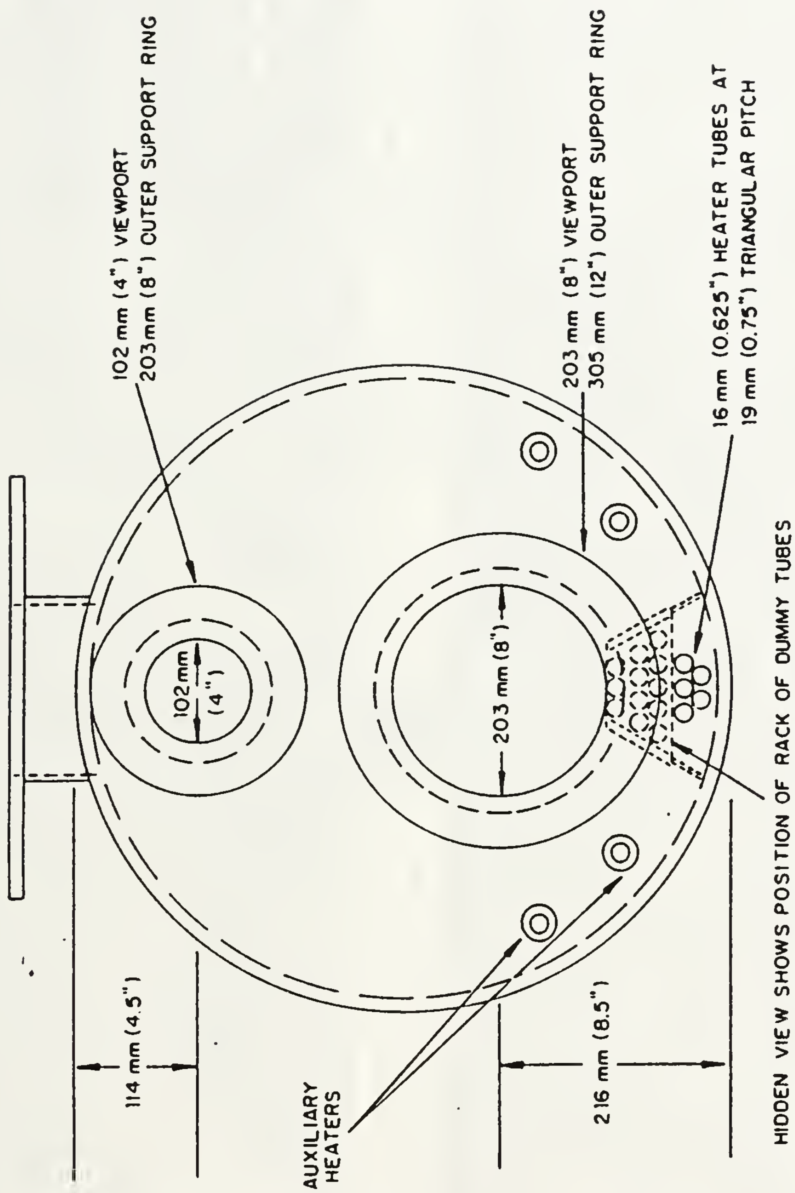

Figure 3. Front View of Evaporator

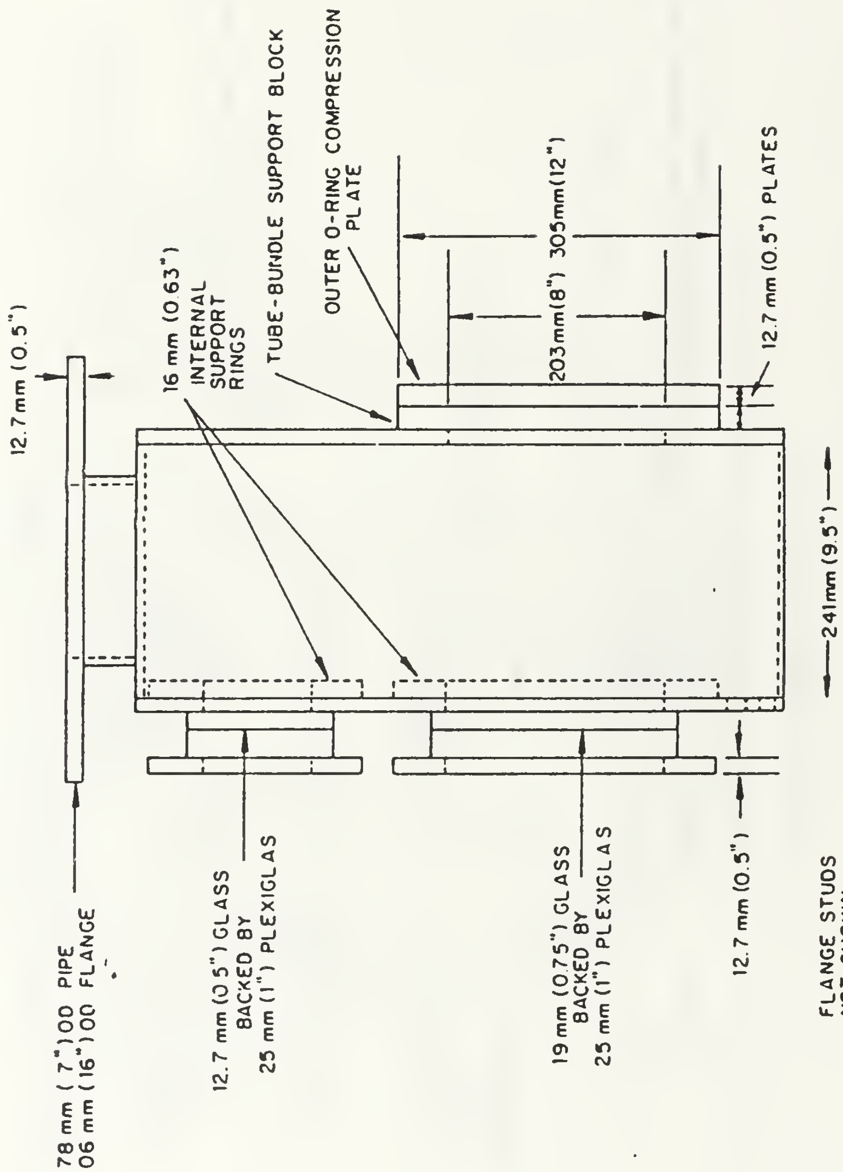

Figure 4. Side View of Evaporator

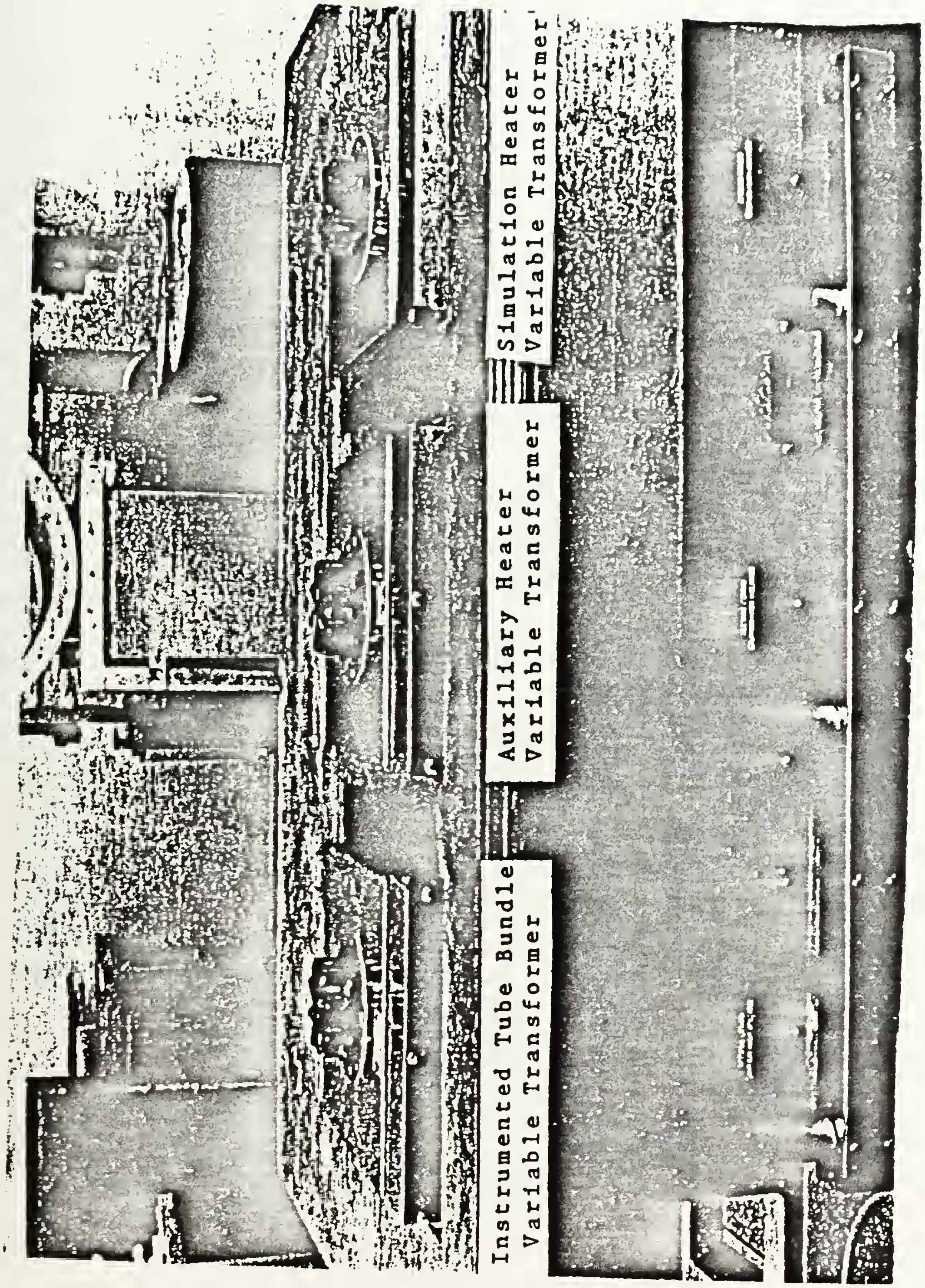

Figure 5. Photograph of 208 V, 75 A, Variable Transformers

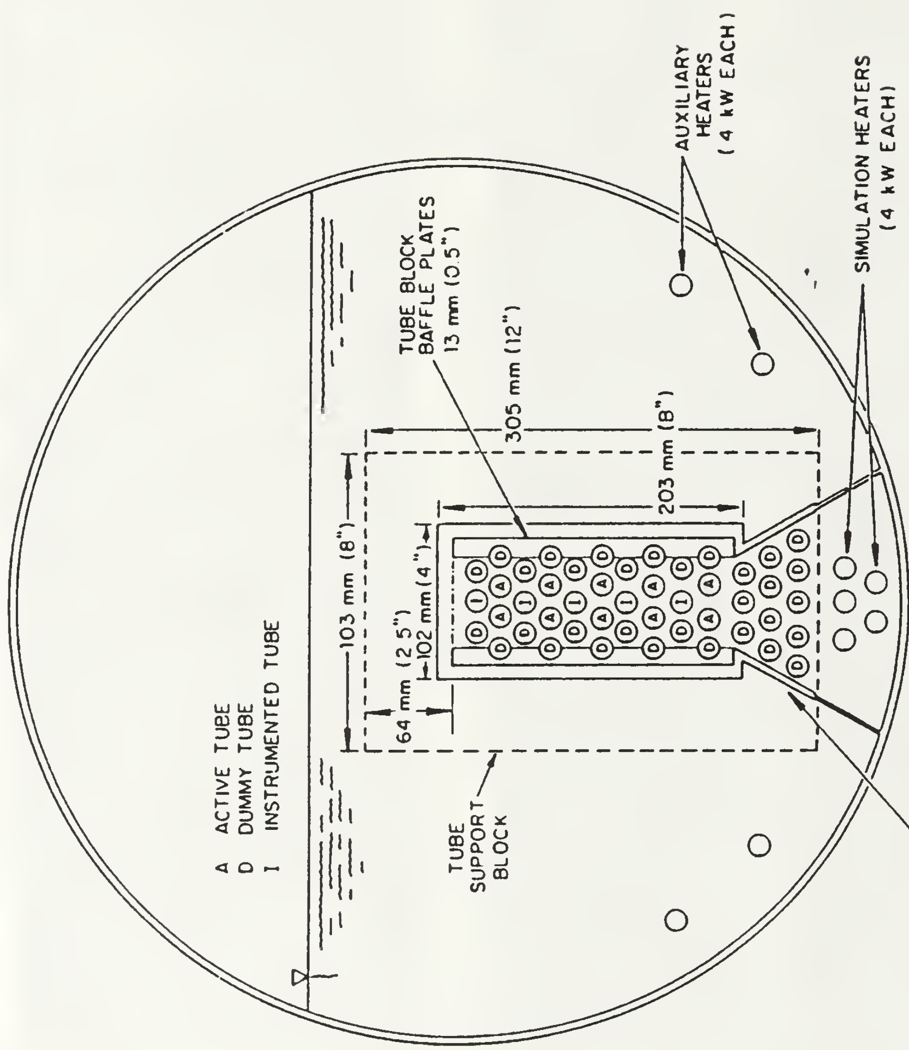

Figure 6. Sectional View of Evaporator Showing Tube Bundle

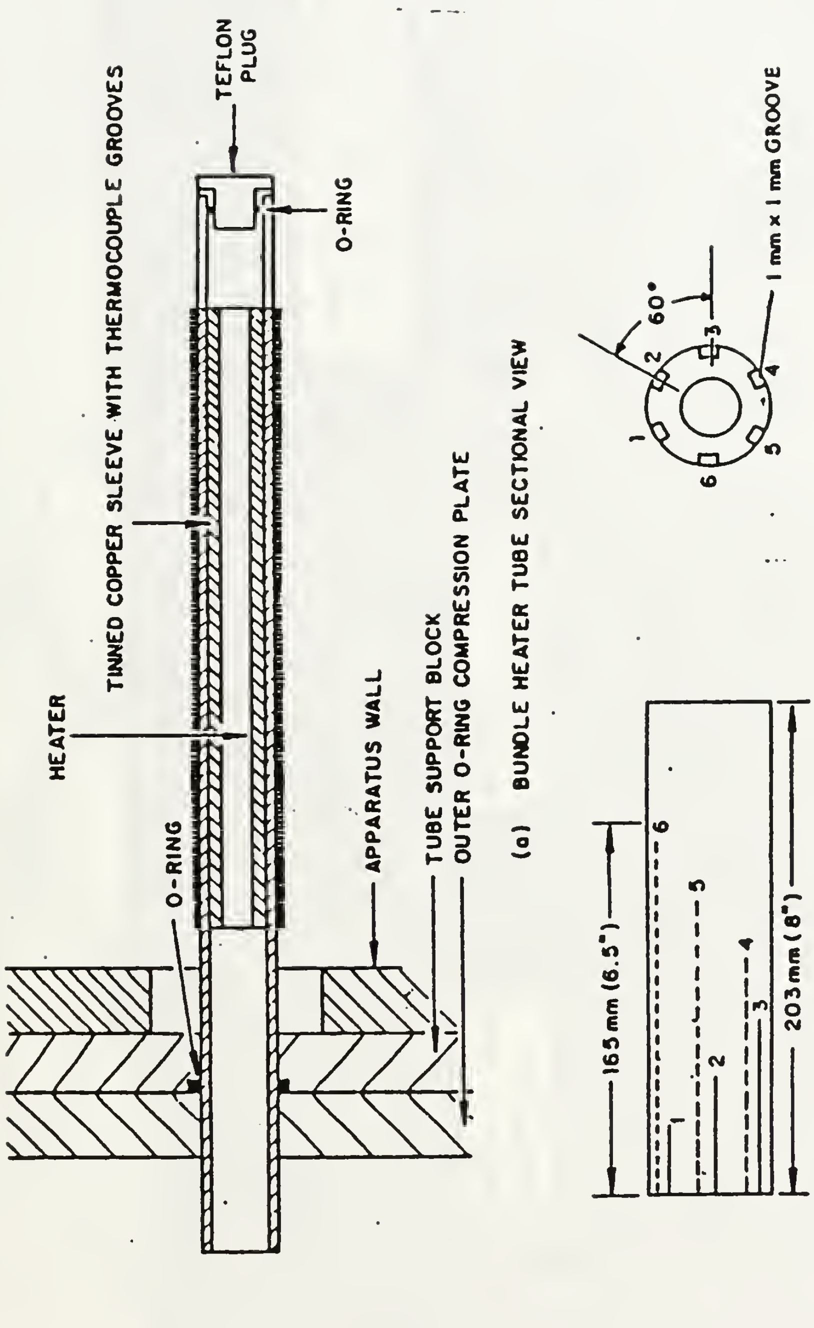

Figure 7. Thermocouple Locations on an Instrumented Boiling Tube and Tube Section View

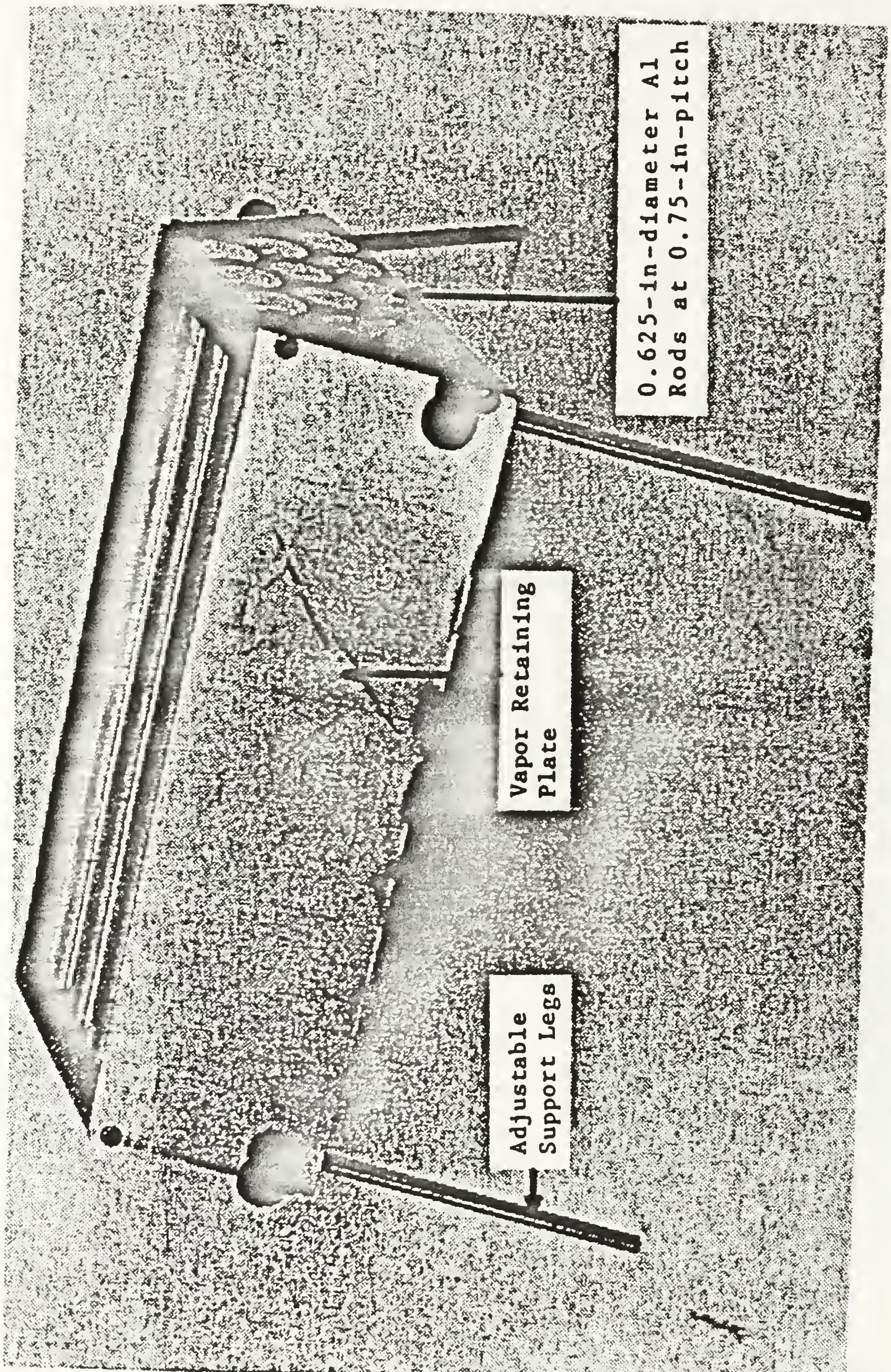

Figure 8. Photograph of Dummy Rack

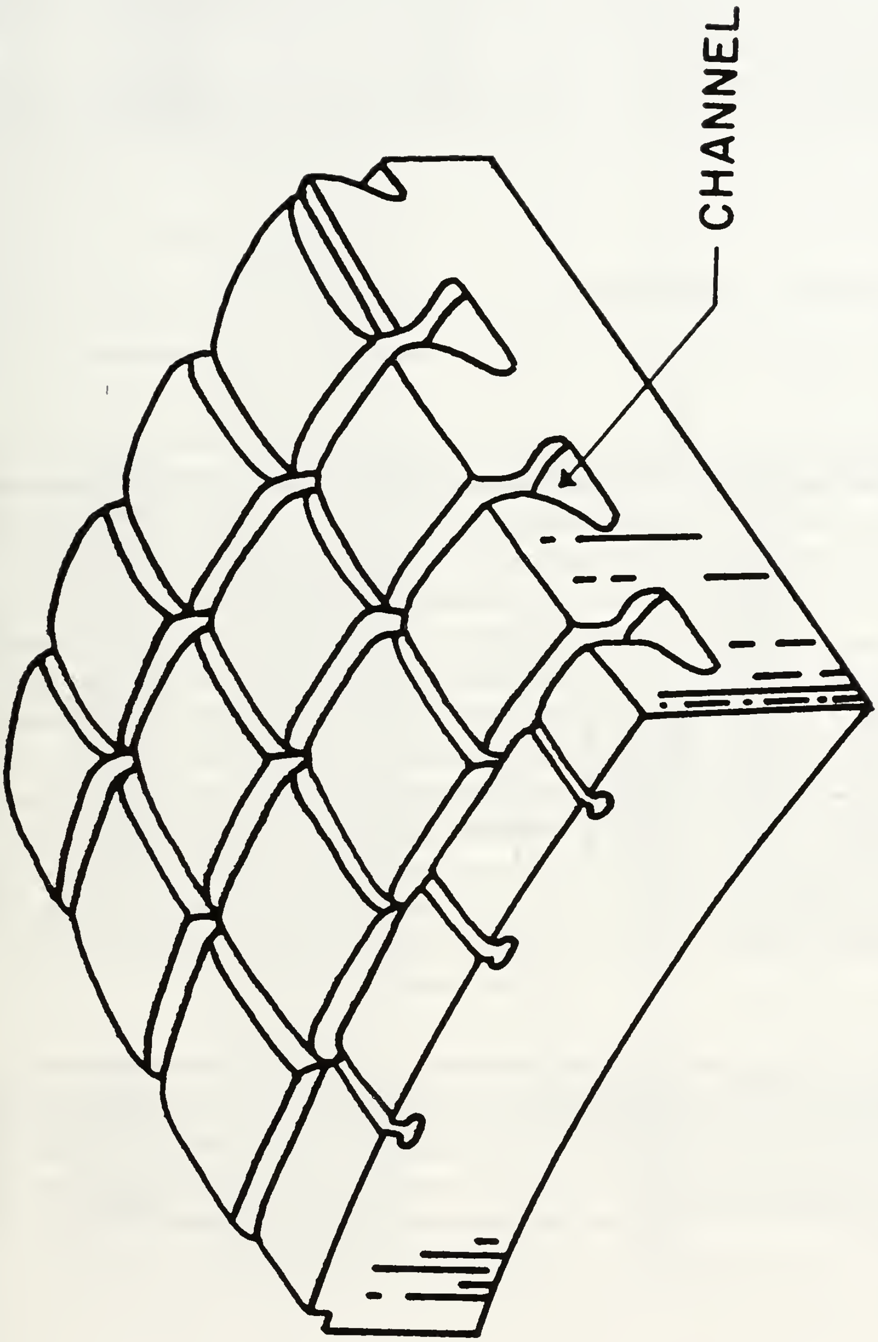

Figure 9. Close-up View of Turbo-B Tube Surface (25 X)

Table 1. EVAPORATOR HEATERS

Heater Type	Number	Power Rating per Heater
Instrumented Tube Heaters	5	1000W
Active Tube Heaters	12	1000W
Auxiliary Heaters	4	4000W
Simulation Heaters	5	4000W

Table 2. COMPUTER/DATA ACQUISITION ASSIGNMENT

Amperage Sensor Description	Channel	Array
Tube 1	30	Amp(0)
Tube 2	31	Amp(1)
Tube 3	32	Amp(2)
Tube 4	33	Amp(3)
Tube 5	34	Amp(4)
Active Heater Group 1	35	Amp(5)
Active Heater Group 2	36	Amp(6)
Active Heater Group 3	37	Amp(7)
Active Heater Group 4	38	Amp(8)
Active Heater Group 5	39	Amp(9)
Auxiliary Heaters	25	Amp(10)
Simulation Heaters	26	Amp(11)

Voltage Sensor Description	Channel	Array
Instrumented/Active	27	Volt(0)
Simulation Heaters	28	Volt(1)
Auxiliary Heaters	29	Volt(2)

Table 2. COMPUTER/DATA ACQUISITION ASSIGNMENT (CONT.)(cont.)

Thermocouple Description	Channel	Array in code
Vapor 1-Top of Condenser	00	T(0)
Vapor 2-Top of Condenser	01	T(1)
Vapor 3-Top of Evaporator	02	T(2)
Liquid 1-Top of bundle	03	T(3)
Liquid 2-Top of bundle	04	T(4)
Liquid 3-Bottom of bundle	05	T(5)
Tube 1,No. 1	40	T(6)
Tube 1,No. 2	41	T(7)
Tube 1,No. 3	42	T(8)
Tube 1,No. 4	43	T(9)
Tube 1,No. 5	44	T(10)
Tube 1,No. 6	45	T(11)
Tube 2,No. 1	46	T(12)
Tube 2,No. 2	47	T(13)
Tube 2,No. 3	48	T(14)
Tube 2,No. 4	49	T(15)
Tube 2,No. 5	50	T(16)
Tube 2,No. 6	51	T(17)
Tube 3,No. 1	52	T(18)
Tube 3,No. 2	53	T(19)
Tube 3,No. 3	54	T(20)
Tube 3,No. 4	55	T(21)
Tube 3,No. 5	56	T(22)
Tube 3,No. 6	57	T(23)
Tube 4,No. 1	58	T(24)
Tube 4,No. 2	59	T(25)
Tube 4,No. 3	60	T(26)
Tube 4,No. 4	61	T(27)
Tube 4,No. 5	62	T(28)
Tube 4,No. 6	63	T(29)
Tube 5,No. 1	64	T(30)
Tube 5,No. 2	65	T(31)
Tube 5,No. 3	66	T(32)
Tube 5,No. 4	67	T(33)
Tube 5,No. 5	68	T(34)
Tube 5,No. 6	69	T(35)

IV. EXPERIMENTAL PROCEDURES

A. REMOVAL OF THE TUBE BUNDLE AND BUNDLE DISASSEMBLY

Before starting the removal of the tube bundle from the evaporator, the front glass viewing windows were carefully removed. Next, all thermocouple wires and tube heater electrical connections were disconnected. After this was completed, the nuts securing the backing plate and support block were removed, and the tube bundle was taken out from the back of the evaporator.

When the bundle needed to be disassembled, it was ensured that there was a clean working surface. The first task was to remove the plexiglas plate attached to one end of the aluminum baffle plates (ie. the front of the bundle assembly) by four screws. The ten screws on the side of each aluminum baffle plate were then removed (these were attached to the dummy tubes down each side of the bundle). The aluminum plates were then pulled off the bundle. The four corner dummy tubes (two top and two bottom) remained attached to the tube bundle support block as they were countersunk into the block. The six outer smooth tubes (three per side) could be easily pulled from the aluminum plates as they were attached only by the screws already removed. The other ten smooth tubes were then unscrewed from the tube bundle support block as seen in Figure 10. The smooth tubes were engraved to ensure proper identification during reassembly. With these tubes and aluminum baffle plates removed, only the instrumented and active enhanced heater tubes remained. These tubes were

removed from the support block by loosening the outer O-ring compression plate, disconnecting the active heater tube wired pairs, and pulling the tubes from the block. Reassembly of the tube bundle is done by reversal of this procedure.

B. SYSTEM CLEAN-UP

If the system had been previously operated with refrigeration oil (or contaminated from some other source) it had to be thoroughly cleaned. To accomplish this, the entire apparatus had to be taken apart and cleaned in the following manner.

After removal of the refrigerant (R-113 by directly draining into 5 gallon drums via drain valve R-5 (see Figure 2 in Chapter 3) at the bottom of the evaporator or R-114 by boiling off into the storage tank by opening R-1 and R-7) and with the system at atmospheric pressure, all electrical connections to the bundle were disconnected and the front viewing glass windows were removed. An electric fan was used for safety to ensure proper ventilation. The tube bundle was then removed and disassembled as described in section A; the dummy tube rack was also removed.

Having removed the tubes from the tube bundle, they were individually washed with warm water, rinsed and then wiped down with acetone. The smooth tubes were cleaned with Copper Brite (a commercial copper cleaning product) to remove any oxidation. They were also wiped down with warm water and then with acetone. The same procedure was followed for the Turbo-B tubes except they were not cleaned with Copper Brite for fear of clogging the channels. During the cleaning process, a soft bristled toothbrush was used to ensure the enhanced surface was cleaned properly,

exercising care not to interfere with the tube surface. The evaporator shell was cleaned in a similar manner, using warm water and acetone.

C. INSTALLATION OF THE TUBE BUNDLE

Once the tube bundle had been cleaned and reassembled (see section A), and before tightening the backing plate nuts, the whole assembly was carefully guided back into the evaporator section, ensuring the plexiglas viewing cover of the tube bundle was not damaged. After the bundle was in position, it was ensured that the dummy tube rack was properly positioned below the bundle and that the vapor thermocouple positions were still 1.75 cm above the bundle. Then, all the nuts were tightened equally on opposite sides to give equal compression on the gasket. To replace the front window, very small, equal torques (using a torque wrench) were applied circumferentially to each nut on the outer ring support in turn. After the window was in place, each tube (which extended through the outer O-ring compression plate) was lightly tapped forward so as to touch the front-viewing window. The backing plate was then tightened and the individual tube O-rings compressed, providing a good seal for the system. The compression plate had grooves for the tube O-rings to sit in to help with proper alignment and ensure a good seal.

D. SYSTEM LEAKAGE TEST

After the system was isolated from the atmosphere and system integrity was restored, a Seargent Welch 10 SCFM vacuum pump was connected to the apparatus (via valves R-1 and R-8) and the pressure taken down to 25 inHg vacuum. Valves R-1 and R-8 were then secured and the system was left

untouched for at least 24 hours to see if there was any air leakage in. If there was significant leakage (>1 inHg over 24 hours), then the vacuum was broken by cracking open valve R-2 slowly (this ensured that no moisture entered the system). The system was pressurized (with air) to 15 psig through valve R-2. Large leaks could then be detected by simply listening to the air issuing from the system; small leaks were detected by spraying a soapy water solution to all surfaces where leaks were most likely to occur (front viewing glass gaskets, backing plate gasket, all fittings/valves coming off the condenser/evaporator, O-ring seals of the bundle tubes etc). Extreme care must be taken to ensure no moisture enters the inside of the heated tubes where the heater wires protrude. After all leaks were detected and corrected, the system was again subjected to a vacuum for another 24 hour period. If the vacuum held, then the system was ready to receive refrigerant. If not, the above leak correction test was repeated.

E. REFRIGERANT

1. Fill

a. From System Storage Tank

A refrigerant storage tank was used to store R-114 during modification/repairs to the system. The storage tank prevented discharge of the R-114 into the atmosphere and made the experimentation less costly. To fill the evaporator with R-114 from the storage tank, the ethylene glycol/water coolant temperature was first reduced to −15 °C. The system pressure was then maintained below the storage tank pressure (vapor pressure of R-114 at 20 °C is approximately 15 psig) by circulation of the

coolant through the condenser test tubes and auxiliary coils. Valves R-6 and R-4 were then opened to draw the R-114 from the storage tank to the evaporator. The amount of refrigerant that was transferred was controlled by throttling valve R-6 to obtain the desired level in the evaporator. If required, additional R-114 could be transferred from a 68 kg storage cylinder to the system using valve R-2 (see section 1.b).

b. From Refrigerant Storage Cylinder

To fill the apparatus from the 68 kg storage cylinder, the system pressure was reduced in the same way as above. A hose assembly containing a Drierite gas purifier was connected between the storage cylinder and valve R-2. A gas purifier was used not only to remove all impurities, but also to remove any water from the refrigerant. Once in place, both the storage cylinder valve and R-2 were opened until the desired refrigerant level was reached in the evaporator.

2. Removal to the Storage Tank

For tube replacement, system maintenance or system clean up, the R-114 was transferred to the storage tank. The ethylene glycol/water coolant temperature flowing through the storage tank was cooled to -15 °C; valves R-7 and R-8 were opened and the vacuum pump was turned on to put the storage tank under vacuum. Once the storage tank was under a 20 inHg vacuum, valve R-8 was shut and valve R-1 was opened. Next R-114 was slowly boiled off to the storage tank by using the tube bundle, simulation and auxiliary heaters at a heat flux of 600 kW/m^2 (slow boiling is important to ensure minimum transfer of oil). As the refrigerant level decreased, individual heaters were turned off to ensure none were uncovered. Once

below the level of the heaters, the final few cm of R-114 was boiled off using heat from the atmosphere. Once all of the R-114 was transferred, valves R-1 and R-7 were shut.

F. OPERATION

1. System Startup, Securing and Emergency Procedures

See Appendix D

2. Normal Operation

The evaporator was filled with R-114 to a level of approximately 10 cm above the top tubes in the bundle. Prior to operating the system, the 8 ton refrigeration unit was run for approximately an hour to reduce the ethylene glycol/water coolant in the sump to a temperature of $-15\ ^{o}C$. The pressure in the evaporator/condenser was usually 12 to 15 psig if the system had been secured overnight. As the sump was brought to temperature, the data acquisition system and computer were turned on. This allowed the temperature in the system to be monitored during cool-down to saturation conditions. With this and pump number one running, one auxiliary condenser coil and the four condenser test tubes were used to bring the pool down to a subcooled condition (for R-114, approximately $1\ ^{o}C$ on <u>all three</u> pool thermocouples). Subcooling of the refrigerant was done to ensure the pool had an evenly distributed temperature prior to starting a run. After reaching this subcooled condition, all coolant supply to the condenser was secured. The pool was then allowed to 'heat up' by conduction from the surroundings. Once a saturation temperature of $2.2\ ^{o}C$ was reached, the instrumented tube(s) (and simulation heaters for test 7) was/were switched on and set to the desired heat flux value.

This lengthy procedure was done to prevent the tubes from prematurely nucleating. The heat flux of the instrumented tubes was then slowly increased at desired intervals by adjusting the rheostat. For increasing heat flux, the data was taken with very small heat flux increments (every 1000 kW/m^2), waiting at least 5 minutes to attain steady state conditions at each heat flux. At all regions of the boiling curve (and especially near the onset of nucleate boiling), two readings were taken at each heat flux to ensure accuracy. The bundle was continuously visually monitored through the observation windows. Figure 11 shows the tube bundle arrangements used during the experimentation. Test one was with only one instrumented tube turned on at any position within the bundle. Test two was with instrumented tubes one and two active in the bundle. Test three was with instrumented tubes one, two and three active in the bundle. Test four was with instrumented tubes one, two, three, and four active in the bundle. Test five was with all five instrumented tubes active in the bundle. Test six was all five instrumented tubes plus all five pairs of active enhanced heater tubes active in the bundle. Test seven was the same as test six with the addition of all five simulation heaters active. For each data set, the five simulation heaters had the same heat flux as the tubes within the bundle.

G. OIL ADDITION

During the bundle experiments, successive amounts of York-C oil were added into the evaporator. Since the weight of the refrigerant in the evaporator was 60.3 kg, the amount of oil corresponding to 1% by weight was measured as 670 ml, 2% 1340 ml etc. The oil was syphoned into the

evaporator via a funnel/hose connection through valve R-3 by reducing the pressure in the evaporator to less than 15 inHg vacuum. Ensuring that no air entered the system, valve R-3 was promptly shut when the desired amount of oil had been added.

H. DATA REDUCTION PROCEDURES

The data reduction program "DRP4RH" was used during the experiments for processing the data collected (see Appendix E for listing). The program was written in HP Basic 3.01 and run on an HP-9000 series computer. The characteristics and capabilities of this software are similar to those provided by Anderson [Ref. 13]. The following modifications were made:

1. Correction for pool height by Chilman [Ref. 3]
2. Installation of new thermocouple at the bottom of the liquid pool (bundle inlet temperature) by Chilman [Ref. 3]
3. The ability to obtain data from one instrumented tube at any position in the bundle.
4. The natural convection correlation of Churchill and Chu [Ref. 31] for a single horizontal cylinder in an 'infinite' liquid pool was added for comparison with experimental data.

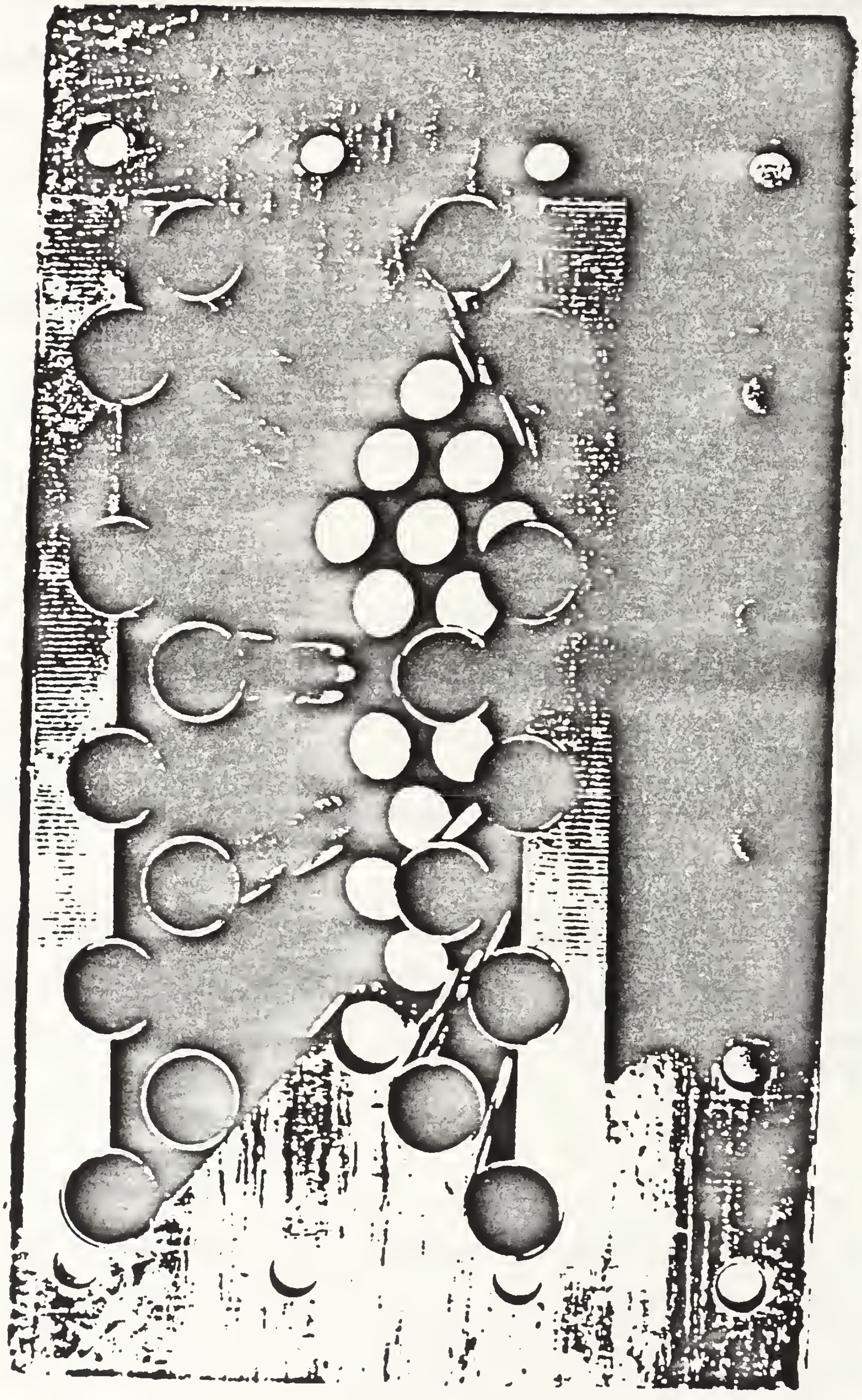

Figure 10. Photograph of Tube Bundle Support Block

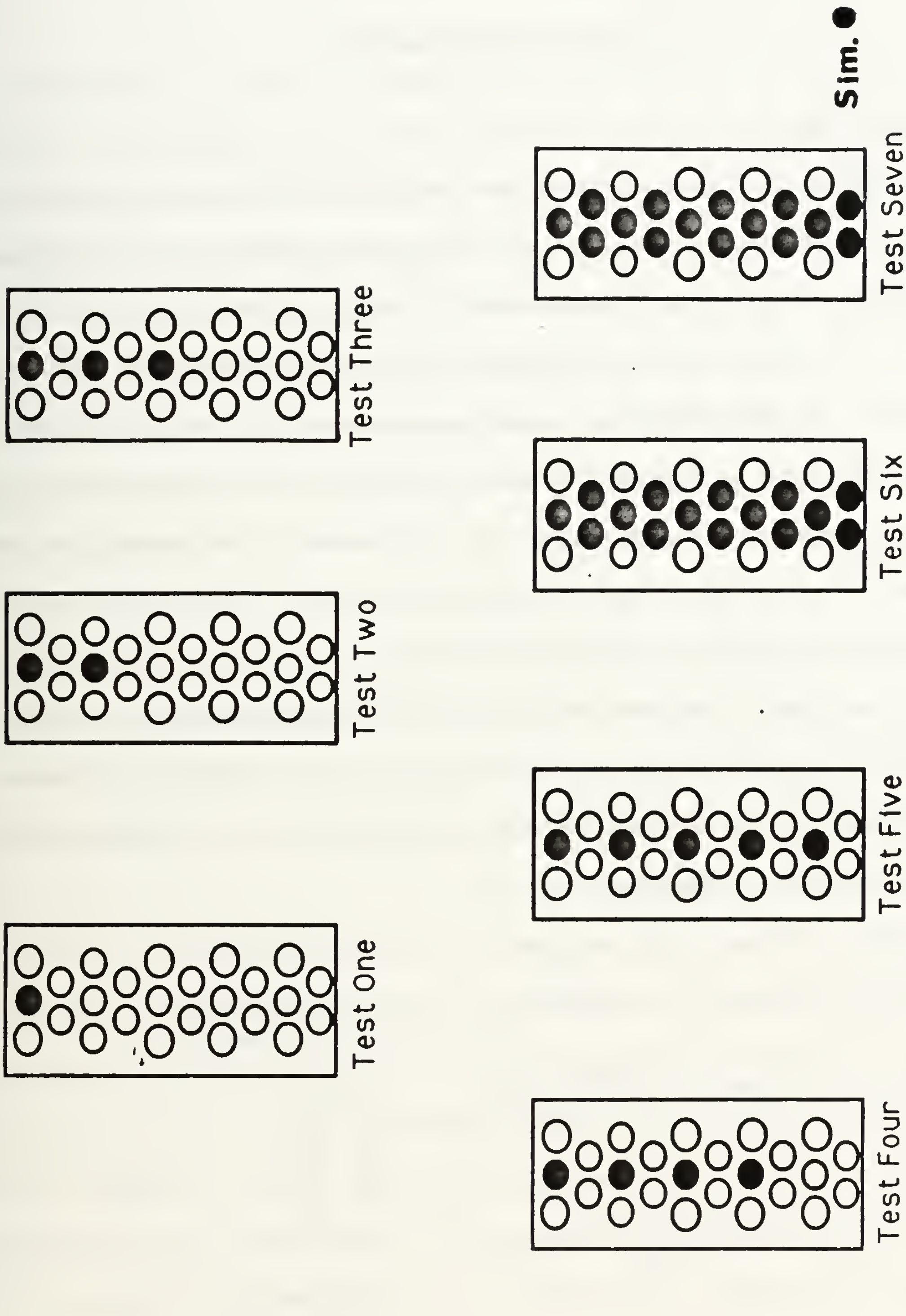

Figure 11. Tube Bundle Arrangements used During Experimentation

V. RESULTS AND DISCUSSION

A. INTRODUCTION

The results are presented in four sections with subs-sections as appropriate. The first section discusses the preliminary experiments which led to modifying the experimental start-up procedure to include subcooling. The second section discusses the natural convection effects, nucleate pool boiling phenomena and hysteresis effects within the tube bundle in pure R-114. The third section discusses similar phenomena for R-114/oil mixtures and their effects on the above. The fourth section shows comparisons of data taken during this thesis with previously obtained data at the Naval Postgraduate School.

A list of data files taken during this investigation may be found in Appendix A. All data files used in this thesis use the following filename sequence. Each file is composed of five sets of alpha-numeric characters used to describe the experiment.

First set (2 char.)	Tube Type	TB (Turbo-B)
Second set (1 char.)	Heat Flux	I (Increasing) D (Decreasing)
Third set (2 char.)	Oil Percent	00 (0%) 01 (1%) 02 (2%) 03 (3%) 06 (6%) 10 (10%)
Fourth set (2 char.)	Test Type	01 (test 1) 02 (test 2) 03 (test 3) 04 (test 4)

05 (test 5)
06 (test 6)
07 (test 7)

Fifth Set (1 char.)   Additional tests A–Z (If conducted)

To give an example, the filename TBI0107 means "Turbo–B tube bundle, increasing heat flux, 1% R–114/oil mixture and test number 7". If more detail is desired about a specific data set, see Appendix A. All plot filenames are similar to data filenames except they start with the letter "P". The test numbers are shown in Figure 11 in Chapter IV.

All graphs are plotted showing heat flux (W/m^2) along the ordinate (y axis) as a function of wall superheat (K) along the abscissa (x axis). The wall superheat is defined as the difference between the 'corrected' average tube wall temperature (ie. having accounted for depth of thermocouple burial) and the local liquid saturation temperature (corrected for hydrostatic head within the bundle). The heat flux was corrected to account for the heat lost through the unheated tube ends. The heat flux was varied from 600 to 100,000 W/m^2 for increasing heat flux. To ensure greater detail at the point of incipience, the heat flux was increased in small steps; these settings varied from test to test. The heat flux values for decreasing experiments were taken at prescribed settings for easy comparison with past experiments and future reference. These heat flux settings were $1x10^5$, $7.5x10^4$, $5x10^4$, $3x10^4$, $2x10^4$, $1.5x10^4$, $1x10^4$, $7x10^3$,$4x10^3$, $2x10^3$, $1x10^3$ W/m^2. Approximately 30–40 data points were taken for each increasing heat flux run and 20–25 points were taken for each decreasing heat flux run.

B. PRELIMINARY EXPERIMENTS

After the pure R-113 was removed following Chilman's [Ref. 3] experiments and the apparatus and system cleaned, pure R-114 was added from the storage cylinders. Five tests were conducted using this R-114 and these are shown in Figure 12. The first test (TBI0001A) was test one with the top tube activated. The procedure described by Eraydin [Ref. 28] was followed, but the plot of test TBI0001A and Eraydin's data for test one (also shown in Figure 12) produced significantly different results in the natural convection (NC) region. The data of Eraydin show a greater heat transfer coefficient (lower wall superheat) than test TBI0001A which show results closer to the Churchill/Chu [Ref. 31] correlation (C/C) for natural convection. The only difference in the apparatus between test TBI0001A and Eyradin's experiments was the addition of a third thermocouple at the bottom of the pool. For test TBI0001A, all three pool temperature readings were within +/- 0.1 ^{o}C prior to recording data. For the data of Eraydin, only the temperature at the top of the pool could be checked.

Test TBI0001B was thought to be a repeat of test TBI0001A, but for the bottom tube in the bundle (tube 5 only). However, upon observation and investigation, it was found that two tubes (tube one <u>and</u> tube five) were activated due to the way the program DRP4 was set up. Hence the data presented is for tube one (the top tube) with tube five (the bottom tube) activated as well. The program was then modified to obtain data for a single tube (test one) at any position within the bundle.

Test TBI0001C was conducted using the bottom tube (tube five) as a single tube. Again following Eraydin's [Ref. 28] procedure, partial

nucleation was observed immediately, explaining why the data lie well to the left of the Churchill/Chu correlation (ie. a higher heat transfer coefficient). It can be seen that test TBI0001C is in good agreement with the single tube of Eraydin (top tube). The reason for this is probably due to the start-up conditions, which were not carefully monitored for any of these tests.

Test TBI0001D was conducted using only tube three and also followed the procedure of Eraydin. This displayed similar behavior as test TBI0001A (tube one) except that nucleation was delayed, ie. occurred at a higher wall superheat.

All experiments thus far were conducted following Eraydin's procedure for pure R-114. It was next decided to vary his procedure slightly. For test TBI0001E, the pool was first subcooled slightly to 1°C. This ensured that any nucleation sites were deactivated and that the whole pool was at an even temperature. The pool was then brought up to the required saturation temperature. However, partial nucleation was still observed during the run. The plot of TBI0001E is similar to test TBI0001C and Eraydin's test one.

With all of these confusing results, it was decided to empty, clean and recharge the evaporator with fresh R-114. Upon boiling off the 'old' R-114, a small quantity of oil contamination was found in the bottom of the evaporator. This could have been either vacuum pump oil (which may have leaked into the apparatus) or refrigerant oil that entered the system with the R-114 charge (which should be minimal). A third possibility could be oil from previous refrigerant/oil mixture experiments. However, this is not likely since the system had been completely stripped and

cleaned twice since the last mixture tests had been conducted. Samples of each type of oil (vacuum pump oil, miscible refrigerant oil (York-C) and a sample of the contamination) were sent away for analysis and the results were still forthcoming at the time of writing this thesis. From the color of the contamination, it would appear to have originated from the vacuum pump. This would seem to be more logical since Chilman had experienced problems with the vacuum pump.

The system, including the bundle, were cleaned thoroughly and fresh R-114 was added. However, a gas purifier was utilized to ensure that only pure, clean R-114 (with no moisture) was added (see Chapter IV for further details). Test TBI0001F then was conducted following Eraydin's [Ref. 28] procedure with no subcooling and 'ignoring' the bottom pool thermocouple value. The data showed good agreement with Eraydin in the natural convection region, but a lower heat-transfer coefficient in the boiling region. A possible explanation for this lower heat transfer is the fact that each individual tube was fully cleaned prior to adding the new R-114 and the surface characteristics may have been modified in some way.

Test TBI0001G was conducted using the same procedure except the pool was initially subcooled down to 1°C for 30 minutes. This ensured the pool had an even temperature distribution throughout. The data were now much closer to the Churchill/Chu [Ref. 31] correlation. However, some premature nucleation was still observed. Test TBI0001J repeated the above test with the pool temperature subcooled to 1°C for at least one hour to further deactivate any remaining nucleation sites within the bundle prior to starting experiments. The data then agreed with the Churchill/Chu correlation as seen in Figure 12. It became apparent that premature

nucleation could affect the natural convection data significantly. Therefore, for all subsequent tests, this same procedure was adopted with strict observation of the bundle to ensure no premature nucleation occurred.

C. PURE R-114 TURBO-B TUBE BUNDLE EXPERIMENTS

1. Test One for Different Tube Positions

The first set of experiments conducted were performance tests in pure R-114. Figure 13 shows increasing heat flux for a single tube within the bundle at different positions (positions 1, 3, and 5) while Figure 14 shows corresponding data (including typical uncertainties) for decreasing heat flux. All three tube positions agree closely with the Churchill/Chu [Ref. 31] correlation in the natural convection region. The difference between position 1 and position 3 and 5 may be that position 1 is affected by the fact that the flow is 'free' to expand after leaving the bundle. This difference may also be due to wall temperature uncertainty due to differences in the fabrication process (see uncertainty analysis Appendix C); however in the natural convection region, this uncertainty is low due to relatively high values of wall superheat. Figure 13 also shows that tube position within the bundle may influence the point of incipience. Bergles and Rohsenow [Ref. 32] have studied the incipient point in more detail. They concluded that nucleation was controlled by a nucleation parameter, N, given by

$$N = \frac{(\sigma)(T_s)(v_{fg})}{(p_v)(h_{fg})}$$

which creates an incipient boiling superheat given by

$$(T_w - T_s) = 2(N)/r.$$

In the above expression, r is the local bubble radius. Calculation of the nucleation parameter for pure R-114 showed that as saturation pressure increases, the nucleation parameter decreases. Assuming that the radius of curvature of the forming bubbles is constant (which is reasonable for a Turbo-B surface which has large, regularly spaced cavities), then (T_w - T_s) also decreases and nucleation may be expected to occur earlier. This certainly seems to be verified in Figure 13 where the incipient point occurs earlier (lower wall superheat) for a lower tube ie. where there is an increase in the local saturation pressure. You et al. [Ref. 33] also showed a decrease (approx. 30%) in the average incipient superheat as pressure was increased from 1 to 1.5 bar for pool boiling of FC-72 on a single tube, offering some other experimental verification for this conclusion.

Chilman [Ref. 3] conducted test one for R-113 using the top tube only and varied the local saturation pressure by varying the pool height in the evaporator. He found that the point of incipience was delayed when increasing the liquid pool height (ie. the hydrostatic pressure head). Boundary layer effects due to different liquid circulation patterns may have caused this delay in nucleation and more research is certainly needed to fully understand the influence of pressure on the point of incipience. One experiment that could be conducted would be to vary the pool height, but keep the local pressure at each tube constant by simultaneously varying the vapor pressure above the pool.

Once nucleation occurs, Figure 13 shows that the single tube experiments merge onto a single boiling curve. In this region, there appears to be no effect of hydrostatic pressure head. Figure 14 shows the corresponding decreasing heat flux data for a single tube at the same three positions within the bundle. It shows no significant influence of tube position in the bundle for decreasing heat flux. Note that at low heat flux, the experimental uncertainty in heat flux and wall superheat is the largest (see Appendix C).

2. Test Two to Test Seven

Figures 15 to 20 show test two to test seven for increasing heat flux with pure R-114. Also shown for comparison in each figure is the Churchill/Chu [Ref. 31] correlation although this is only truly valid for a single tube in an infinite pool. Figure 15 shows good agreement with the Churchill/Chu correlation in the natural convection (NC) region and shows no effect of the lower tube on the upper tube. The incipient point occurs approximately at the same wall superheat for both tubes; once boiling the lower tube has the higher heat-transfer coefficient. This is contrary to the results obtained by Chilman [Ref. 3] and Anderson [Ref. 13] with pure R-113, where the higher tube had the better heat transfer. The reason for this difference is not known, but may be due to the explosive nature of incipience for R-114 compared to the more gradual partial incipience for R-113. For R-114 experiments, the pool was subcooled by 1 °C for only about hour while for the R-113 experiments, the pool was left in a subcooled state since the previous experiment (for R-113 experiments, the pool is 'heated up' to saturation conditions). This

difference in subcooling may significantly affect the nature of the observed incipience. Further research should be conducted at the incipient point to address some of the questions. Figure 16 for three tubes activated shows similar behavior as Figure 15 (ie. during nucleate boiling, the lowest tube has the highest heat-transfer coefficient). Also, Figure 16 shows that the lowest tube seems to nucleate last. Figures 17 and 18 for four and five tubes activated show similar trends in both the NC and boiling regions. It appears that the tubes nucleate in order down the bundle (ie. the top tube nucleates at the lowest wall superheat and the bottom tube nucleates at the highest wall superheat). For tests six and seven (Figures 19 and 20 respectively), the maximum controllable heat flux was less than tests one through five due to the use of smooth tubes in the condenser limiting the condensate rate (and hence pressure) in of the vapor space (if enhanced tubes had been used, this could have been increased). Figure 19 (test six) is consistent with the above trends. Furthermore, the effect of activating the whole bundle seems to cause the lowest tube to nucleate at a lower heat flux and wall superheat. It also appears that there may be some influence of tube position in the boiling region; however, this is probably due to inaccuracy in the wall temperature measurements (see Appendix C). When the simulation heaters are also activated (test seven, Figure 20) the trends in the NC region are similar (ie. no effect of lower tubes on upper tubes). Full nucleation of the bundle however, seems to occur earlier.

Figure 21 shows the data from tube one for all seven tests with increasing heat flux. This figure is of more fundamental interest as it shows the same tube under different bundle conditions. It therefore gives

a better direct comparison of the effect of heated lower tubes as any uncertainty in the tube wall measurements (the largest error in the experimental data) is the same for each test (ie. any effects seen in the data are bundle effects). In the NC region, tube one alone (test one) is somewhat different. This may be due to 'expansion' of the flow as it leaves the top of the bundle (ie. where the velocity of the flow has slowed down) or due to convective effects by the addition of another tube. For test two, Figure 21 shows an effect of the lower tube on tube one performance in the NC region. For test three and all subsequent tests no further improvement is seen. It appears, therefore that in the natural convection region, an upper tube is affected by a lower tube directly below; however, when additional lower tubes are heated, there is no further increase in performance of the top tube. There is also no effect on the incipient point (apart from test one mentioned above). In the high heat flux boiling region, there is also little enhancement due to the lower tubes. This is to be expected in an enhanced tube bundle, where the total heat transfer at high heat fluxes is primarily due to nucleation from the tube surface itself, rather than from convection around the surface from the tubes below.

Figures 22 to 27 show tests two to seven for decreasing heat flux in pure R-114. When comparing tube one to tube two, Figure 22 shows a increase in heat transfer performance of tube one by tube two in the boiling region while Figure 15 (increasing heat flux) showed the opposite effect. The most probable reason for this crossover is that these two experiments (TBI0002) and (TBD0002) were conducted on different days and startup procedures were slightly different. For TBI0002 (increasing heat

flux), the test was conducted as outlined in Chapter IV section F (ie. subcooled to 1 °C, gradually heated up with data taken over a period of approximately 4 hrs). For TBD0002 (decreasing heat flux), the pool was subcooled to 1 °C, and then tube one and two were turned on to the highest heat flux (10^5 W/m^2) and allowed to heat up for 30 minutes. The total time boiling for TBI0002 at the highest heat flux was therefore less than for TBD0002. For all other experiments, increasing followed by decreasing runs were conducted on the same day approximately 15 minutes apart. More research should be conducted to investigate nucleation site activation/deactivation.

At high heat fluxes for test three, Figure 23 shows no heat transfer performance improvement between the tubes. However, at low heat fluxes, there does appear to be an improvement on tube one and two from tube three. Figures 24 to 27 show similar trends at high and low heat fluxes (ie. the top tubes are further enhanced by lower tubes at low heat fluxes). It should also be noted that the lowest tube in any specific decreasing heat flux test had the worst performance.

Figure 28 compares tube one only for tests one to seven for decreasing heat flux. As stated above, there appears to be a definite tube enhancement at low heat fluxes with little or no enhancement at high heat fluxes. This is probably due to convective effects which tend to increase the heat transfer performance of the upper tubes due to the presence of lower tubes (ie. bubbles coming from the lower tubes impinge and slide over the upper tubes and increase the heat transfer). At high heat fluxes, on the other hand, all the tubes are nucleating so vigorously that these 'sliding' bubbles have little or no noticeable affect on the

overall performance. This supports the hypothesis of Cornwell [Ref. 7] that total heat transfer in a bundle is due to a summation of convective and nucleation heat transfer phenomena. Similar trends were found by Anderson [Ref. 13] and Akcasayar [Ref. 25] for smooth and finned tube bundles respectively (using the same apparatus) and also by Arai et al. [Ref. 20] for a Thermoexcel-E tube bundle. However, Akcasayar [Ref.] did not find such an enhancement effect for a High Flux tube bundle indicating that at low heat fluxes, a porous coated surface already has a significant number of active nucleation sites such that impinging bubbles from below have little or no added effect. Turbo-B is more similar to a Thermoexcel-E surface and at low heat fluxes, these two types of surface obviously exhibit different nucleation characteristics to those of a porous coated tube.

D. R-114/OIL MIXTURES TURBO-B TUBE BUNDLE EXPERIMENTS

1. Tests with 1% and 2% oil

Only four experiments were conducted with a 1% and 2% R-114/oil mixture. These were tests one and seven for both increasing and decreasing heat flux; no experiments were conducted for tests two through six. Figure 29 shows test one at 1% oil concentration for increasing and decreasing heat flux, clearly showing a hysteresis pattern. Compared with pure R-114 (Figures 13 and 14), Figure 29 shows no apparent effect of oil on the heat transfer in either the NC or boiling regions.

Figure 30 shows test seven for increasing heat flux (1% oil). Compared with Figure 20 (pure R-114), there are similar trends (ie. no

effect in the NC or boiling regions). The tubes again appear to be nucleating 'in order' down the bundle, as found with test seven in pure R-114. For decreasing heat flux, Figure 31 shows similar trends to test seven in pure R-114 (Figure 27). Thus a 1% oil concentration appears to have little or no effect on bundle performance for both increasing and decreasing heat flux.

Figure 32 shows test one for a 2% oil concentration for increasing and decreasing heat flux. Figures 33 and 34 show test seven for increasing and decreasing heat flux respectfully for 2% oil concentration. All three graphs (Figures 32 to 34) are similar to those for pure and 1% oil concentrations, showing that 2% oil also has little effect on overall bundle heat transfer performance.

2. Tests with 3% oil

Nine experiments were conducted with a 3% R-114/oil mixture. In addition to test one and seven (conducted for both increasing and decreasing heat flux as before), tests two through six were conducted for decreasing heat flux only. Figure 35 shows test one with 3% oil for both increasing and decreasing heat flux. Again, the figure clearly shows hysteresis effects between the increasing and decreasing experiments. As with previous oil percentages (Figures 13, 14, 29, and 32), it shows there is no apparent effect of oil in the NC region, similar to previous test one data for other oil percentages. However, at the highest heat flux (100 kW/m^2) there is an <u>increase</u> in the heat transfer of about 10%. This is similar to the increases found by Burkhardt and Hahne [Ref.23] in a finned tube bundle and Arai et al. [Ref. 20]. Figure 36 shows test seven

for increasing heat flux. The Churchill/Chu [Ref. 31] correlation for pure refrigerant is plotted for comparison only. Agreement is good, demonstrating that in the NC region, in addition to there being no effect of tube position, there is also no apparent effect of oil concentration on the heat-transfer coefficient. As before, the tubes appear to be nucleating 'in order' (ie. top tube nucleates first with the bottom tube nucleating last).

Figures 37 to 42 show data from tests two to seven for decreasing heat flux only. All show no effect of lower tubes on upper tubes (within the bundle) in the boiling region at high heat fluxes (the small amount of scatter is probably due to inaccuracies in the wall temperature measurements). Each successive figure shows that the lowest tube has the lowest heat-transfer coefficient; this tube is then enhanced by the activation of tubes below it. Again it should be noted that the experimental uncertainty is larger at low heat fluxes. At all oil concentrations, tube five is seen to have the lowest heat transfer performance. According to Chilman [Ref. 3], tube five had the highest uncertainty in the wall temperature measurements and this might be the cause of this discrepancy.

If one compares Figure 42 for 3% oil with Figure 28 for pure R-114, it can again be seen that there is a small increase in the bundle heat-transfer coefficient for the R-114/oil mixture at the highest heat fluxes. For all tests with oil added, significant foaming was observed at the pool surface and this may be the cause of this increase in heat transfer. Schlager et al. [ref. 21] in their review article point out that for certain conditions (typically low pressure and high heat flux),

the heat-transfer coefficient increases at low oil concentrations; they attributed this to foaming. Figure 43 compares test one to seven for tube one for decreasing heat flux. As before with pure R-114 (Figure 28), there appears to be a definite increase in performance of the upper tubes by lower tubes at the low heat fluxes due to convection effects, with little or no such increase at high heat fluxes.

3. Tests with 6% oil

The same nine tests as with 3% oil were conducted with a 6% R-114/oil mixture. Figure 44 shows test one for both increasing and decreasing heat flux. It clearly shows a hysteresis 'loop' between increasing and decreasing experiments. In comparison with other oil concentrations, the point of incipience occurs at a slightly lower heat flux. There also appears to be a small degradation in performance (10-15% compared with 3% oil concentration) at the highest heat flux (100 kW/m^2) due to the oil, but there is no apparent effect in the NC region. Figure 45 shows test seven for increasing heat flux. As before, there is no apparent effect of oil on the heat transfer in the NC region and the tubes appear to be nucleating 'in order'. The point of incipience also seems unaffected by the presence of the oil.

Figures 46 to 51 show tests two to seven for decreasing heat flux. At the highest heat fluxes, there is a similar small degradation in the heat transfer as found with test one (10-15%) when compared with a 3% oil concentration (Figures 37 to 42). When compared with pure R-114 (Figures 22 to 27), there is neither enhancement nor degradation, indicating that any enhancement provided by 3% oil is offset by 6% oil.

At low heat fluxes, the data are not only very similar to that for pure refrigerant, but also to the other R-114/oil mixtures (ie. at low heat fluxes, there is no effect on heat transfer at any oil concentration). Figure 52 compares tests one to seven for tube one for decreasing heat flux. As before, there appears to be the same convective enhancement at low heat fluxes with no enhancement (due to the successive activation of lower tubes within the bundle) at high heat fluxes.

4. Tests with 10% oil

The same nine tests were repeated for an R-114/oil mixture with 10% oil. Figure 53 shows test one for both increasing and decreasing heat flux. Incipience occurred at a slightly heat higher flux than both 3% and 6% oil concentrations indicating that there appears to be no systematic increase or decrease in this point with increase in oil concentration. More importantly, there is a significant decrease in the heat transfer at the highest heat fluxes (20%) when compared with pure R-114. This is probably due to the re-entrant channels becoming 'clogged' with oil as the R-114/oil mixture is 'transported' to the surface at a high rate. Figure 54 shows test seven for increasing heat flux. As before, this shows that the NC region is unaffected by either oil concentration or lower tubes in the bundle. At the highest heat fluxes available (40 kW/m^2) there appears to be little decrease in the bundle performance (when compared to pure R-114) due to the oil. This indicates that at typical evaporator operating heat fluxes, the presence of oil does not significant effect the heat transfer enhancement process. At higher

heat fluxes, however, the effect of oil appears to be very significant as seen in Figure 53.

Figures 55 to 60 show test two to test six for decreasing heat flux with 10% oil. At low heat fluxes, there seems to be no effect of the oil on the local heat transfer performance. However, at high heat fluxes, there is a significant decrease in performance. Interestingly, if one compares Figures 53, and Figures 55 to 58 at high heat fluxes, the lowest activated tube in the bundle is significantly degraded. The effect of activating a lower tube significantly enhances the heat transfer from the tube directly above and (to a lesser degree) the tubes even higher in the bundle. This may be due to the vigorous boiling action of lower tubes partly 'scouring' the oil rich layer which 'blankets' the upper tubes. This effect was also noticeable with the High Flux bundle (Akcasayar [Ref. 25]).

Figure 61 compares tube one for tests one to seven for decreasing heat flux. If one compares Figures 26 (0%), 43 (3%), 52 (6%) and 61 (10%) for tube one for all seven tests, it is clear that at low heat fluxes, the heat transfer coefficient is similar, regardless of oil concentration. Furthermore, convective effects are consistent and provide similar enhancements in heat transfer performance for all concentrations. At high heat fluxes at 0, 3, and 6% oil concentrations, there is little enhancement due to activation of lower tubes. However, at 10%, there does appear to be a small heat transfer enhancement due to activation of lower tubes. This was attributed above to increased 'scouring' of the oil from the vicinity of the Turbo-B surface by the increase in bubble activity as more tubes are activated within the bundle. However, for a practical

operating heat flux range between 15 and 30 kW/m^2, there is no significant degradation in heat transfer performance for an oil concentration of up to 10%.

E. COMPARISON OF R-114/OIL MIXTURE EXPERIMENTS

Figures 62 and 63 compare tube one from test one for increasing and decreasing heat flux for all oil concentrations. Figure 62 shows no effect of oil in the NC region, but some degradation in the boiling region. The correlation of Churchill/Chu is included for comparison. The incipient point appears relatively random, indicating no early or delayed nucleation caused by the presence of oil. Figure 63 shows similar degradation with a significant effect of the oil (20% decrease in the heat transfer from 0% to 10% oil) at the highest heat fluxes.

Figures 64 and 65 compare tube one from test seven for increasing and decreasing heat flux for all oil concentrations. As compared to tube one test one (Figures 62 and 63), the presence of oil has some degradation effect on the heat transfer performance (15%) in the NC region; this may be due to a change in the mixture properties which would tend to increase the wall superheat slightly as shown. As with Figure 62, Figure 64 shows that the incipient point appears relatively random. Figure 65 shows similar trends to Figure 63 (ie. no effect of oil at high heat fluxes), but shows convective effects at low heat fluxes. This was expected and previously reported (Figures 28, 43, 52, and 61).

Figures 66 and 67 show the average bundle heat-transfer coefficient (ie. an average of all five instrumented tubes) as a function of heat flux for test seven for increasing and decreasing heat flux respectively at all

oil concentration. The data are from the same data set as that shown in Figures 64 and 65. Comparing Figures 64 and 66, degradation is seen in the NC region (15%) due to the change in mixture properties as mentioned above. However, at a practical operating heat flux range between 15 and 30 kW/m^2, the presence of up to 10% oil causes no degradation in bundle performance as seen. These trends over this heat flux range were similar to that found for a High Flux tube bundle (Akcasayar [Ref. 25]). Comparing Figures 65 and 67, similar trends (ie. no significant effect of oil) are found. However, due to the limit in maximum controllable heat flux for test seven, data at 'higher' heat fluxes (up to 10^5 W/m^2) could not be obtained (as mentioned earlier). As shown in Figures 62 and 63, there may be a significant degradation in the heat transfer performance at these higher heat fluxes.

F. COMPARISON WITH PREVIOUS NPS DATA

Figure 68 shows a comparison between the present data for a Turbo-B bundle, the data of Anderson [Ref. 13] for a smooth tube bundle and the data of Akcasayar [Ref. 25] for both a 19 fpi and High Flux tube bundle in R-114. For clarity, only test one (tube one) for a decreasing heat flux in pure R-114 has been shown. Figure 68 shows that the Turbo-B tube has a significantly lower heat-transfer coefficient than the High Flux tube at all heat flux. This is surprising since Sugiyama [Ref. 34] showed that in the single tube apparatus, the Turbo-B tube was the best performer. The reason for this difference in behavior is not known. Also, all of the data appear to be parallel to each other; one may expect the enhanced tubes to have a different slope to a smooth tube due to the greater amount of

nucleation. At the highest heat fluxes, Turbo-B and the 19 fpi tube appear to have a similar heat transfer performance. However, the finned tube heat flux is based on the root diameter; if the actual finned area had been used, then the heat flux would be significantly lower. Figure 68 shows that the heat transfer enhancement given by the Turbo-B tube when compared to a smooth tube is about three at high heat fluxes and increases to about five at low heat fluxes.

Figures 69 and 70 compare the average bundle heat-transfer coefficient (ie. test seven) for a given oil percentage to that with no oil for all four tube bundles at heat fluxes of 15 and 30 kW/m^2 respectively. 15 and 30 kW/m^2 were chosen as being representative of the lower and upper limits of heat fluxes used in practical Naval evaporators. At 15 kW/m^2, Figure 69 shows large enhancements for the smooth and finned tube bundles for all oil concentrations, especially at the lower oil concentrations. However, the Turbo-B and High Flux tube bundles show a degradation in the heat-transfer coefficient at all oil concentrations (approximately 5-10% at low oil concentrations dropping to nearly 25% at 10% oil for the High Flux bundle). At the higher heat flux (30 kW/m^2), Figure 70 shows similar trends as Figure 69. However, the High Flux bundle now exhibits a 40% decrease in the average bundle heat-transfer coefficient at 10% oil.

Figures 71 and 72 compare the average bundle heat-transfer coefficient (ie. test seven) for each enhanced tube to that for the smooth tube bundle (tested by Anderson [Ref. 13]) for all oil concentrations at heat fluxes of 15 and 30 kW/m^2 respectively. At 15 kW/m^2 with pure R-114, Figure 71 shows an enhancement factor of 3.7 for the Turbo-B tube bundle. This enhancement decreases slowly with increasing oil percentage to a factor of

about 2.5 at 10% oil. This agree very closely with the 19 fpi bundle. The High Flux bundle exhibits much larger enhancements, from over 6 at 0% oil to just over 3 at 10% oil. At 30 kW/m^2 with pure R-114, Figure 72 shows an enhancement of 3.8 for the Turbo-B tube bundle, decreasing to about 3 at 10% oil. This again agrees closely with the 19 fpi bundle. It should be noted that the High Flux bundle enhancement has decreased to a similar value and gets worse than the other bundles as the heat flux is further increased.

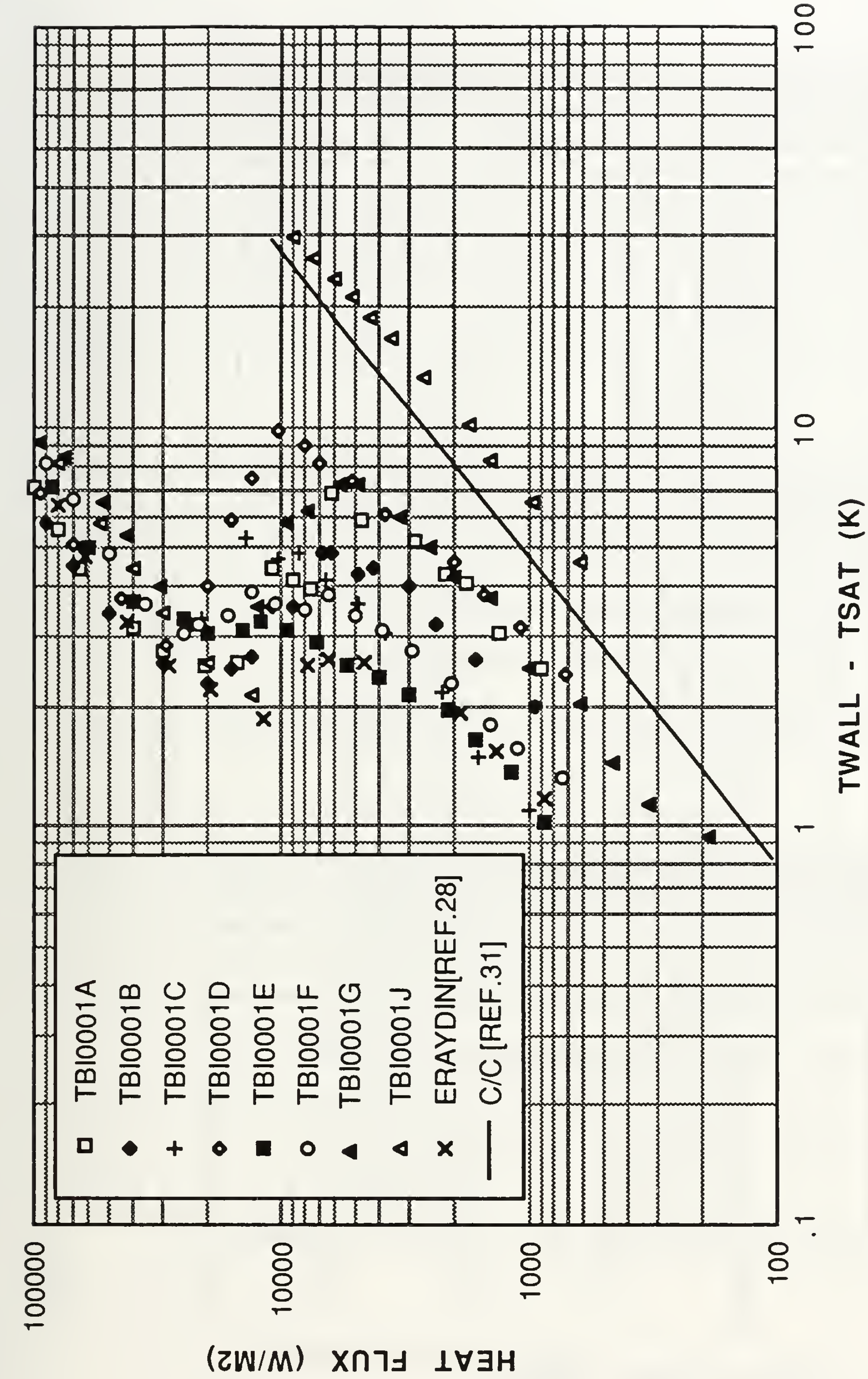

Figure 12. Performance of Test One For Preliminary Experiments

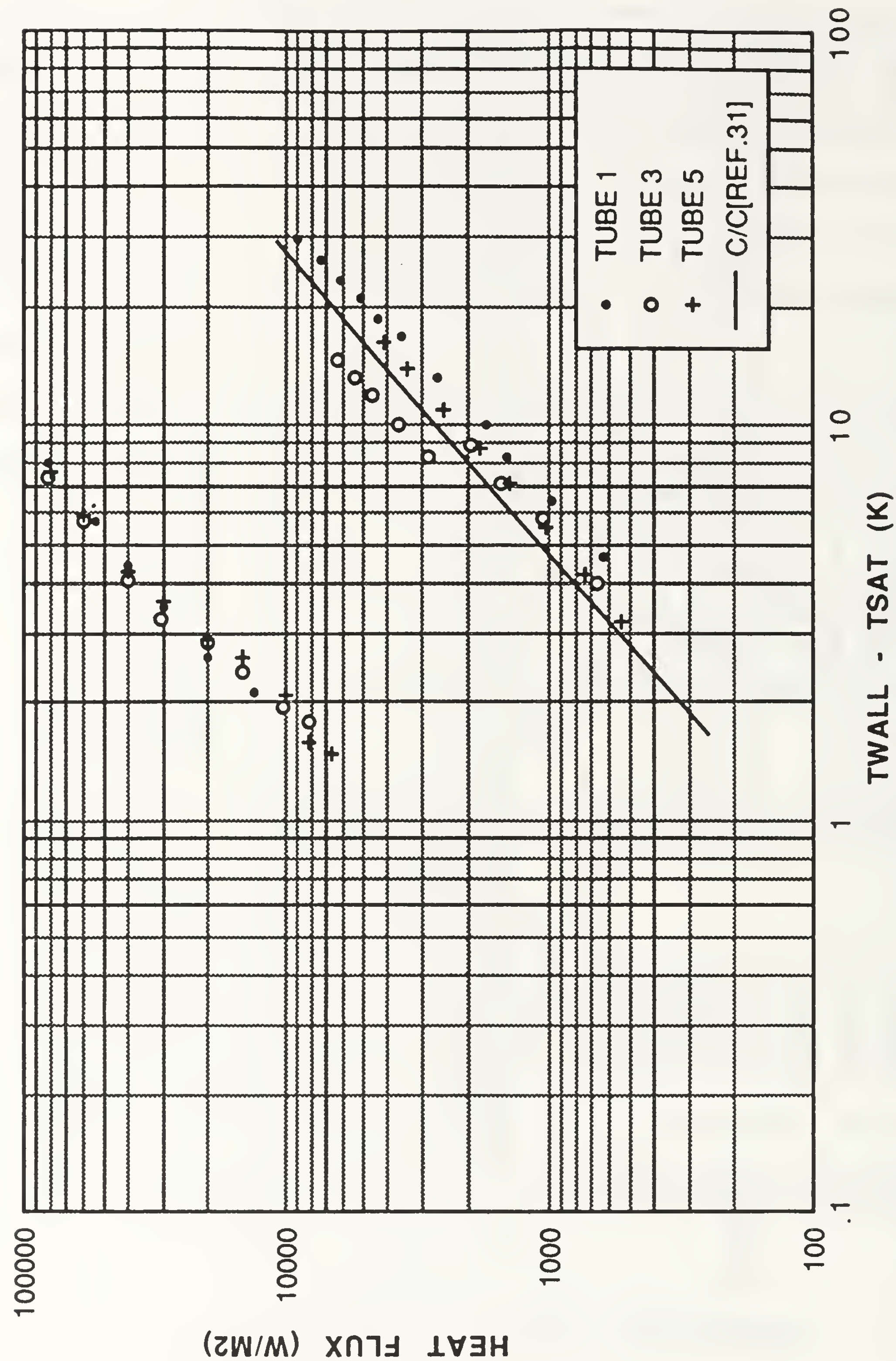

Figure 13. Performance of Test One at Various Tube Positions for Increasing Heat Flux

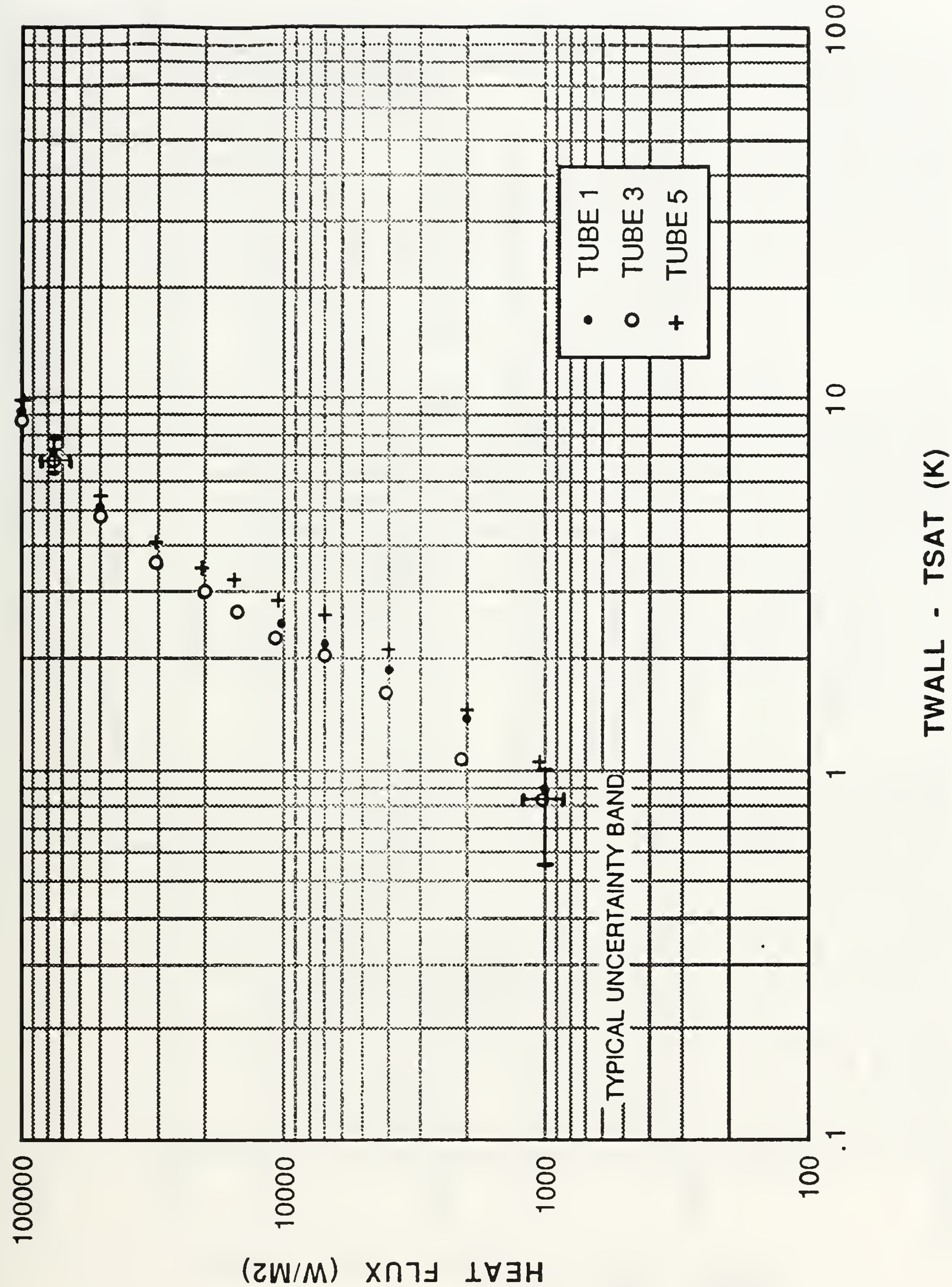

Figure 14. Performance of Test One at Various Tube Positions for Decreasing Heat Flux

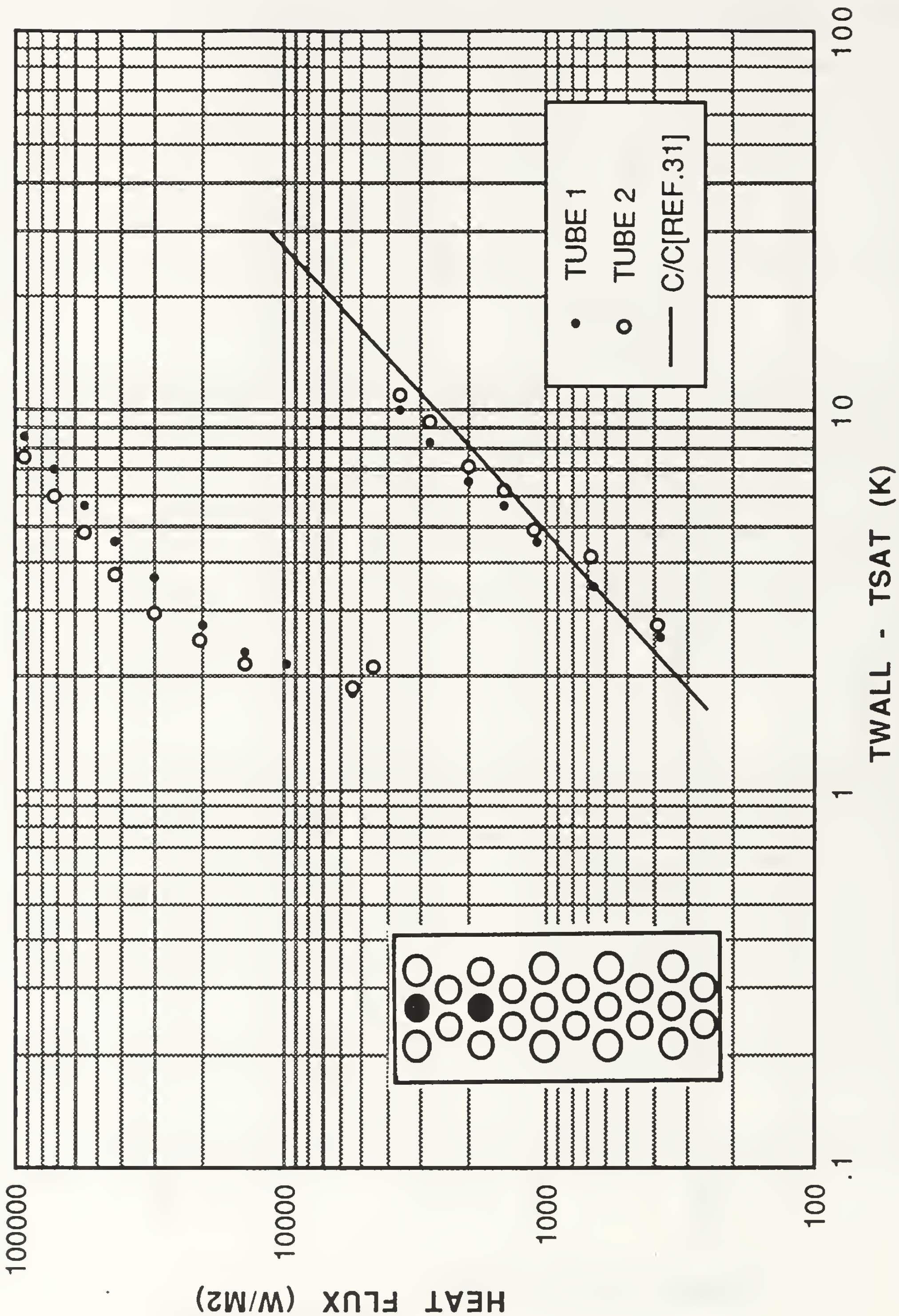

Figure 15. Performance of Tubes 1 and 2 for Increasing Heat Flux in Pure R-114

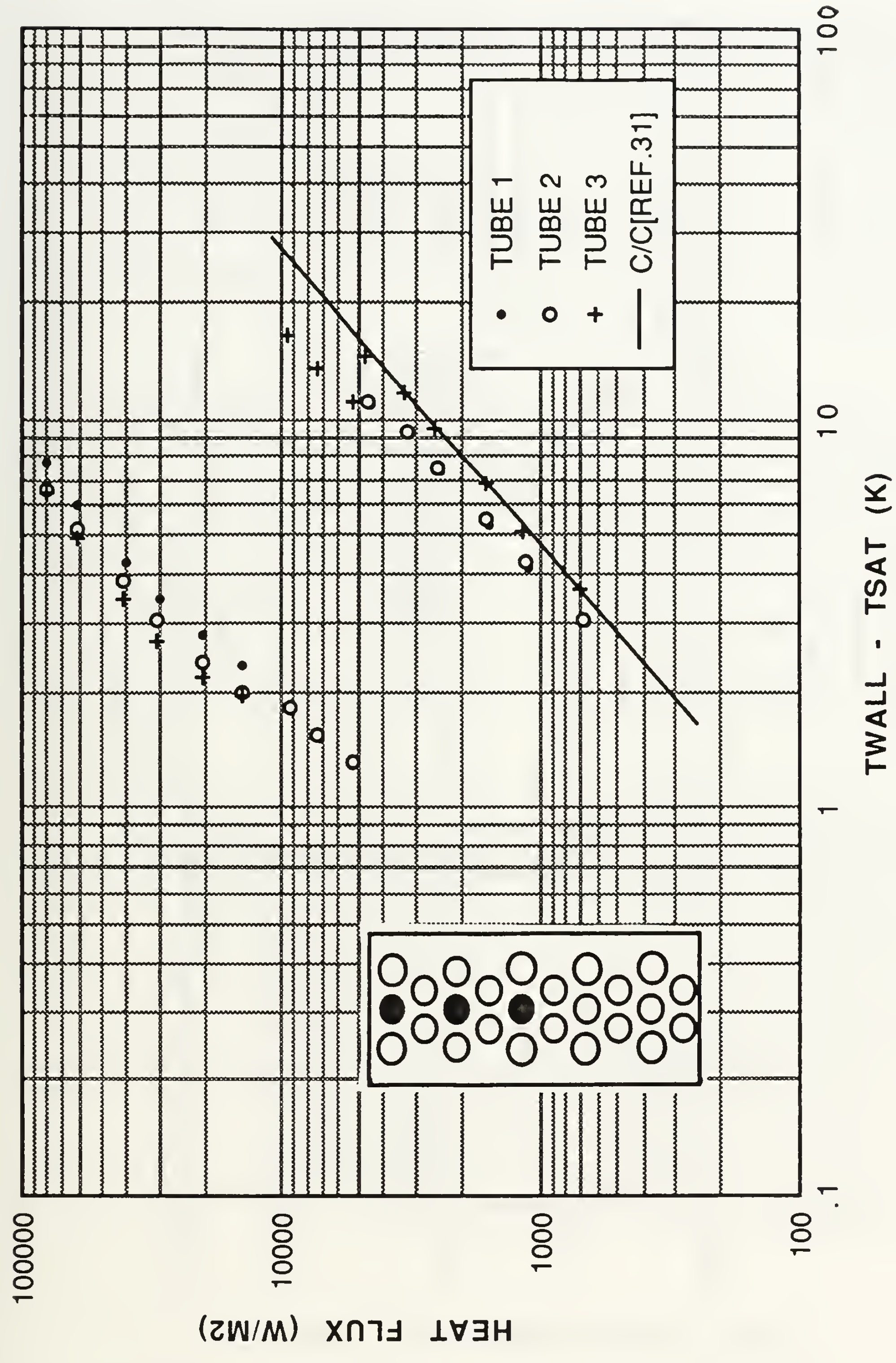

Figure 16. Performance of Tubes 1, 2, and 3 for Increasing Heat Flux in Pure R-114

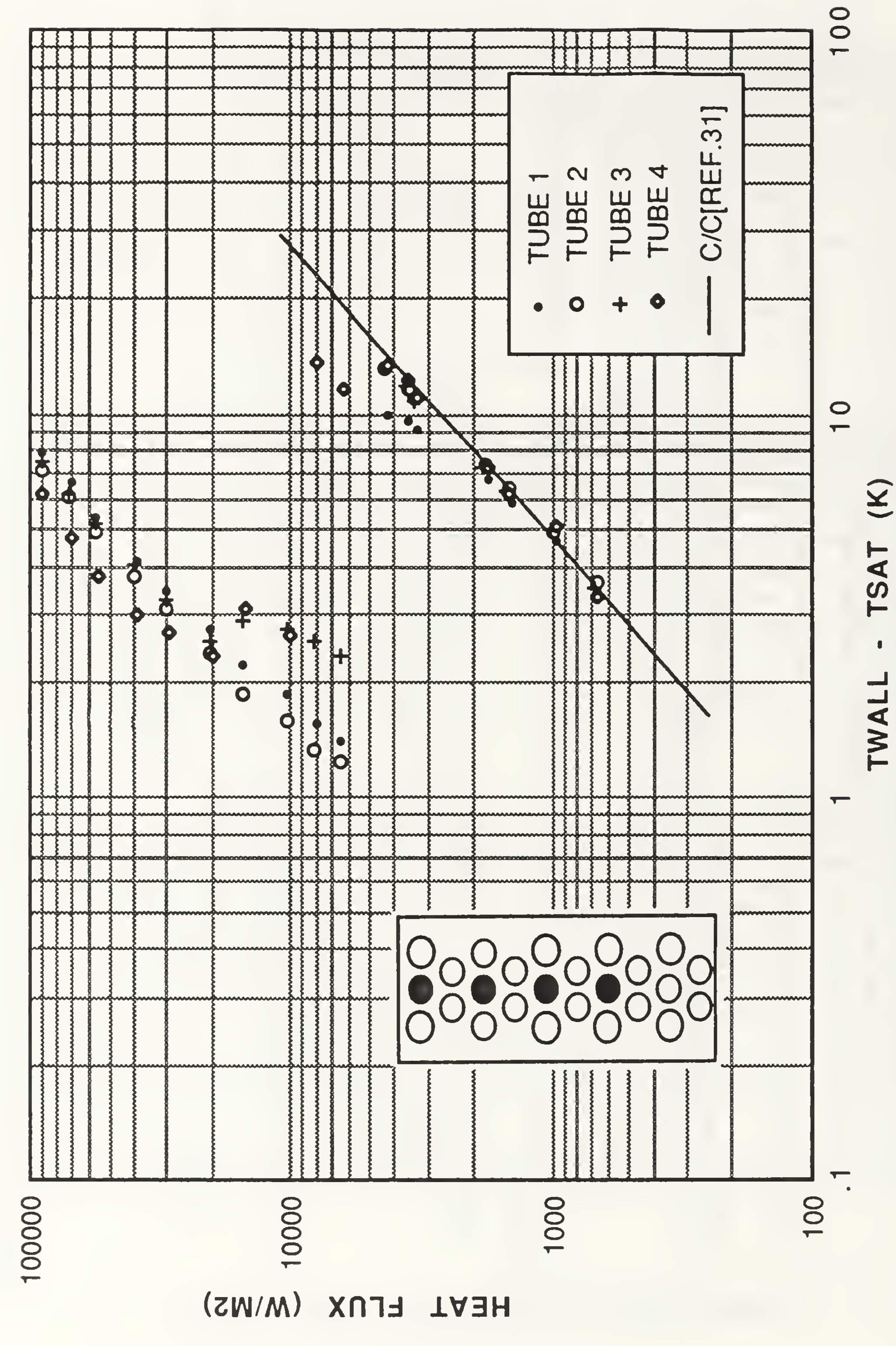

Figure 17. Performance of Tubes 1, 2, 3, and 4 for Increasing Heat Flux in Pure R-114

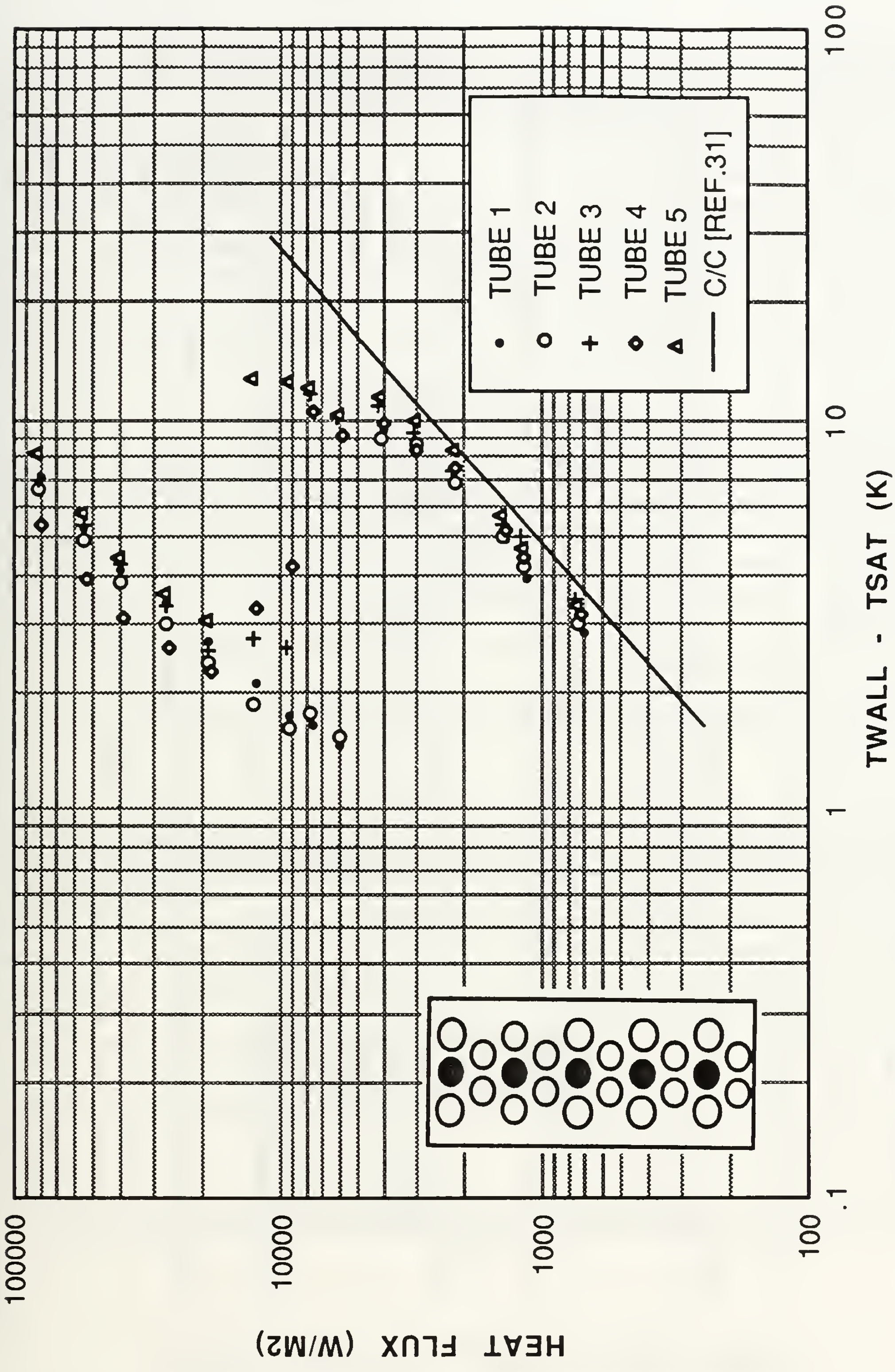

Figure 18. Performance of All Five Tubes for Increasing Heat Flux in Pure R-114

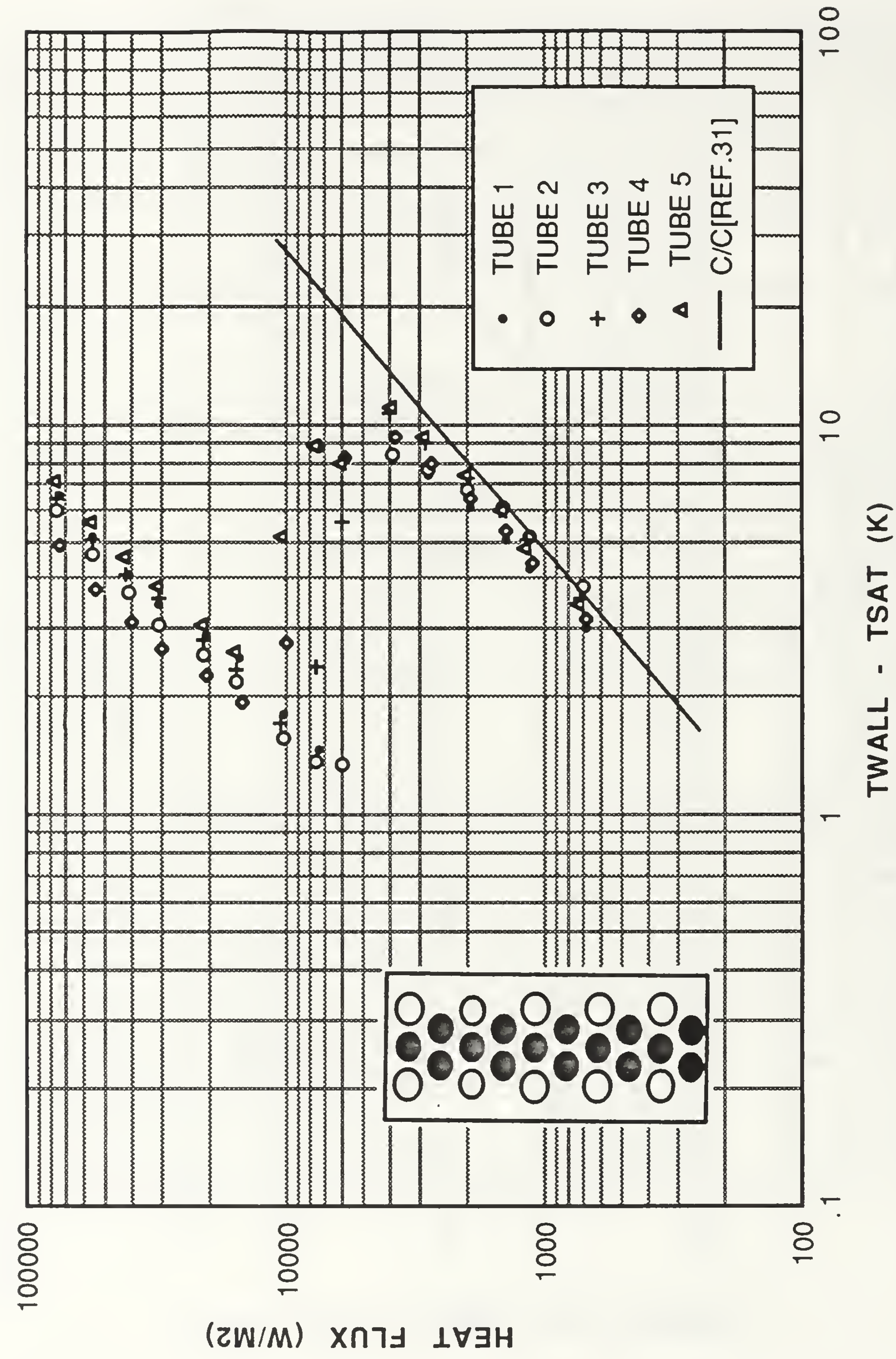

Figure 19. Performance of All Five Tubes with Active Pairs for Increasing Heat Flux in Pure R-114

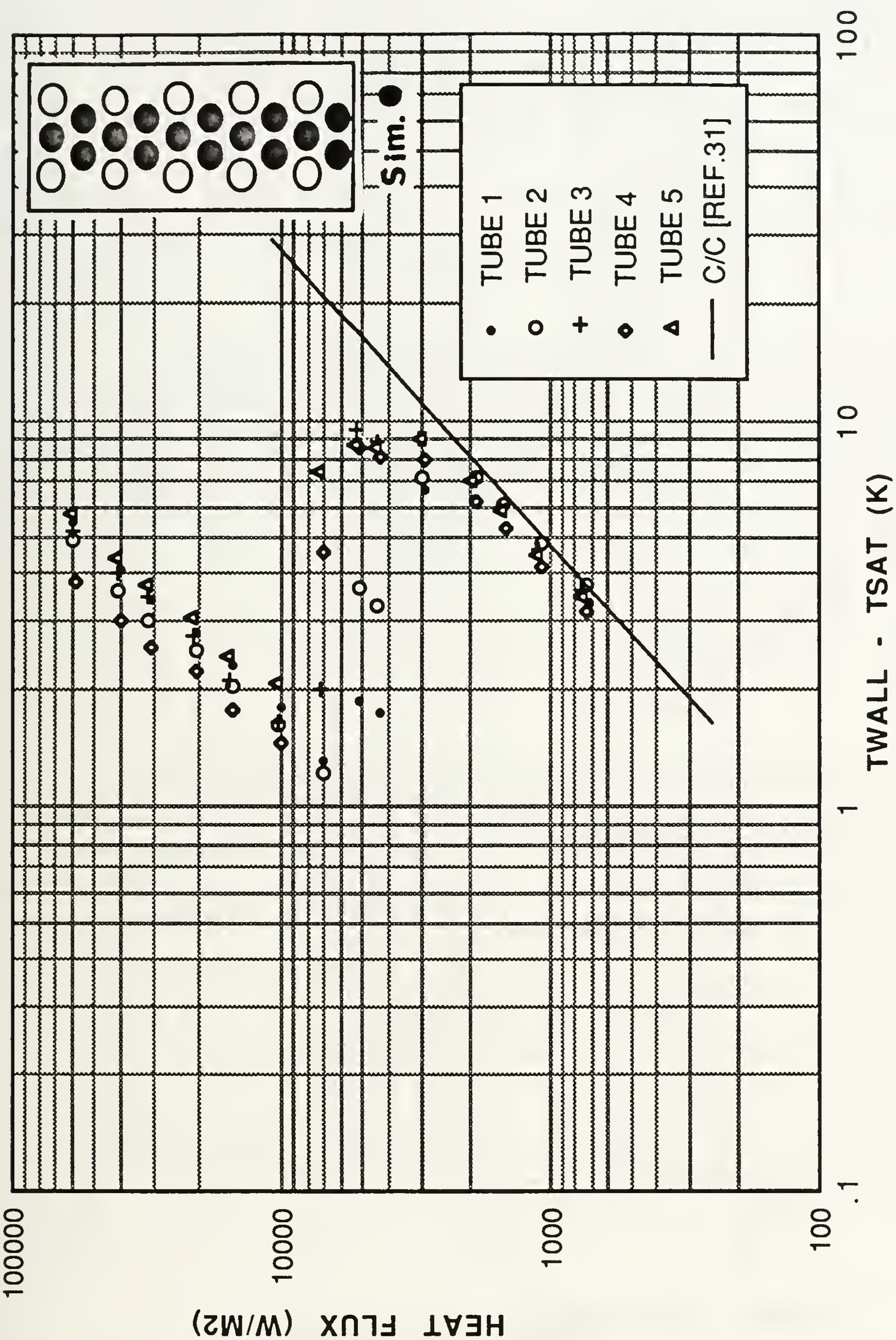

Figure 20. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in Pure R-114

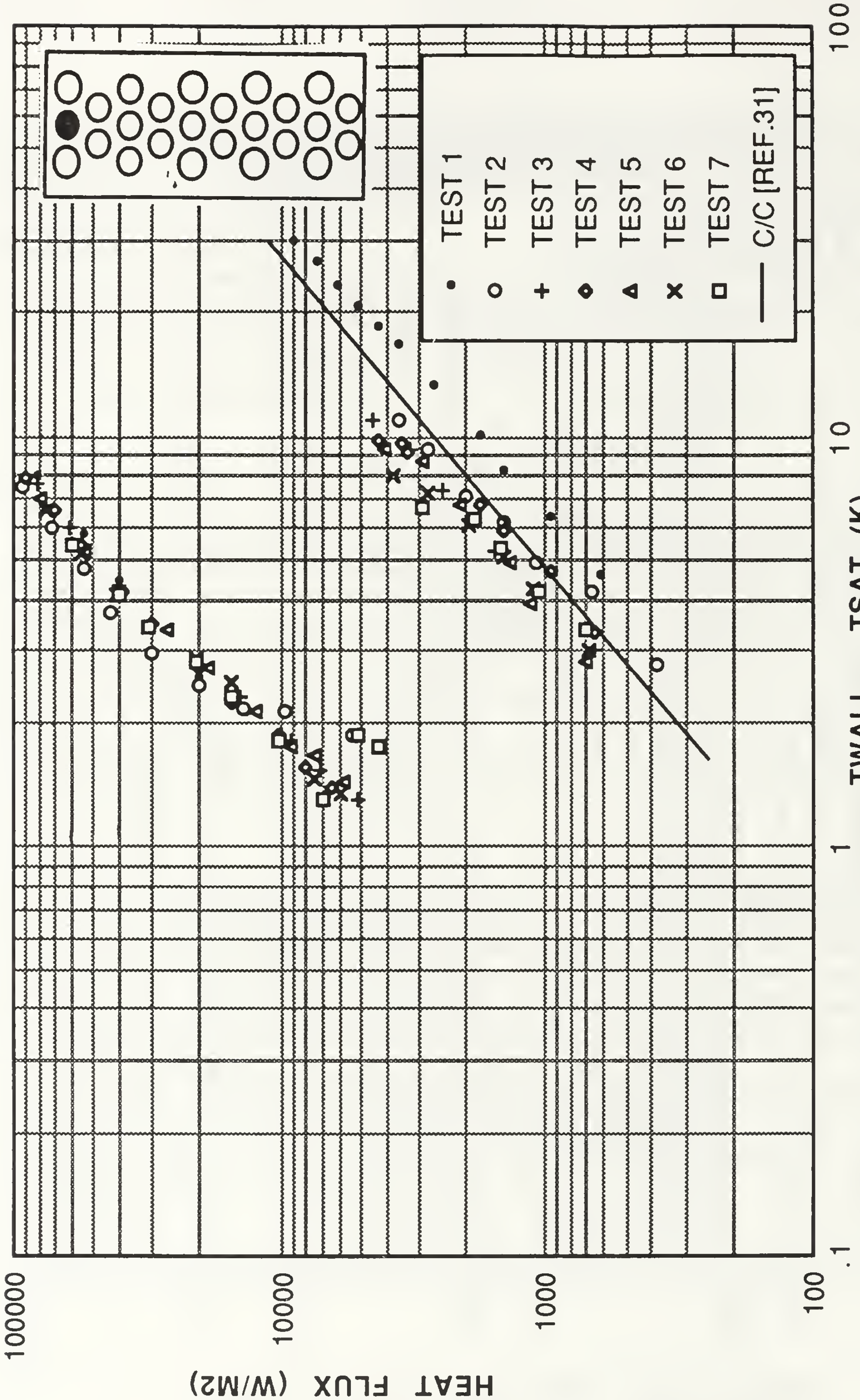

Figure 21. Comparison of Tests One to Seven for Tube 1 for Increasing Heat Flux in Pure R-114

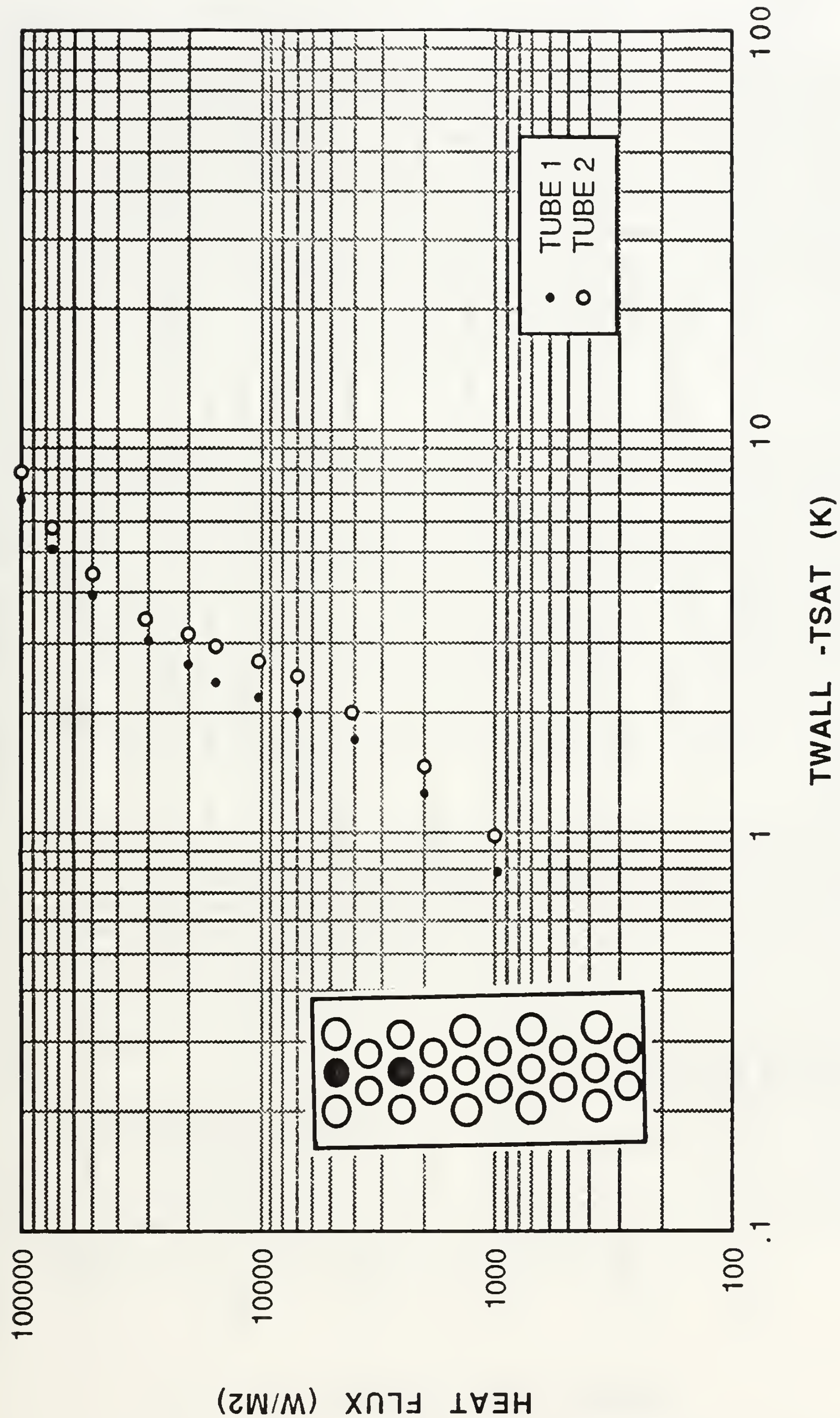

Figure 22. Performance of Tubes 1 and 2 for Decreasing Heat Flux in Pure R-114

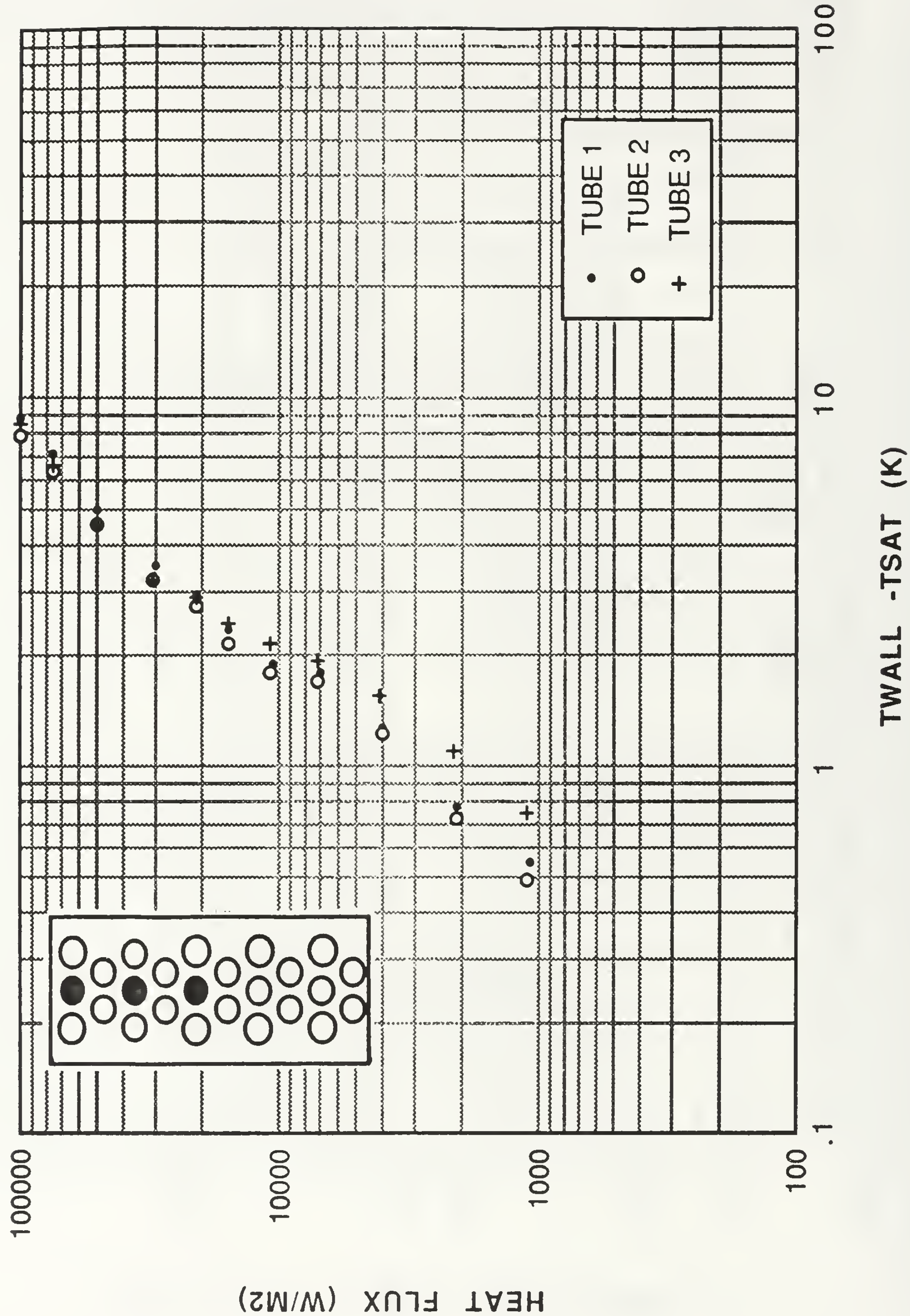

Figure 23. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in Pure R-114

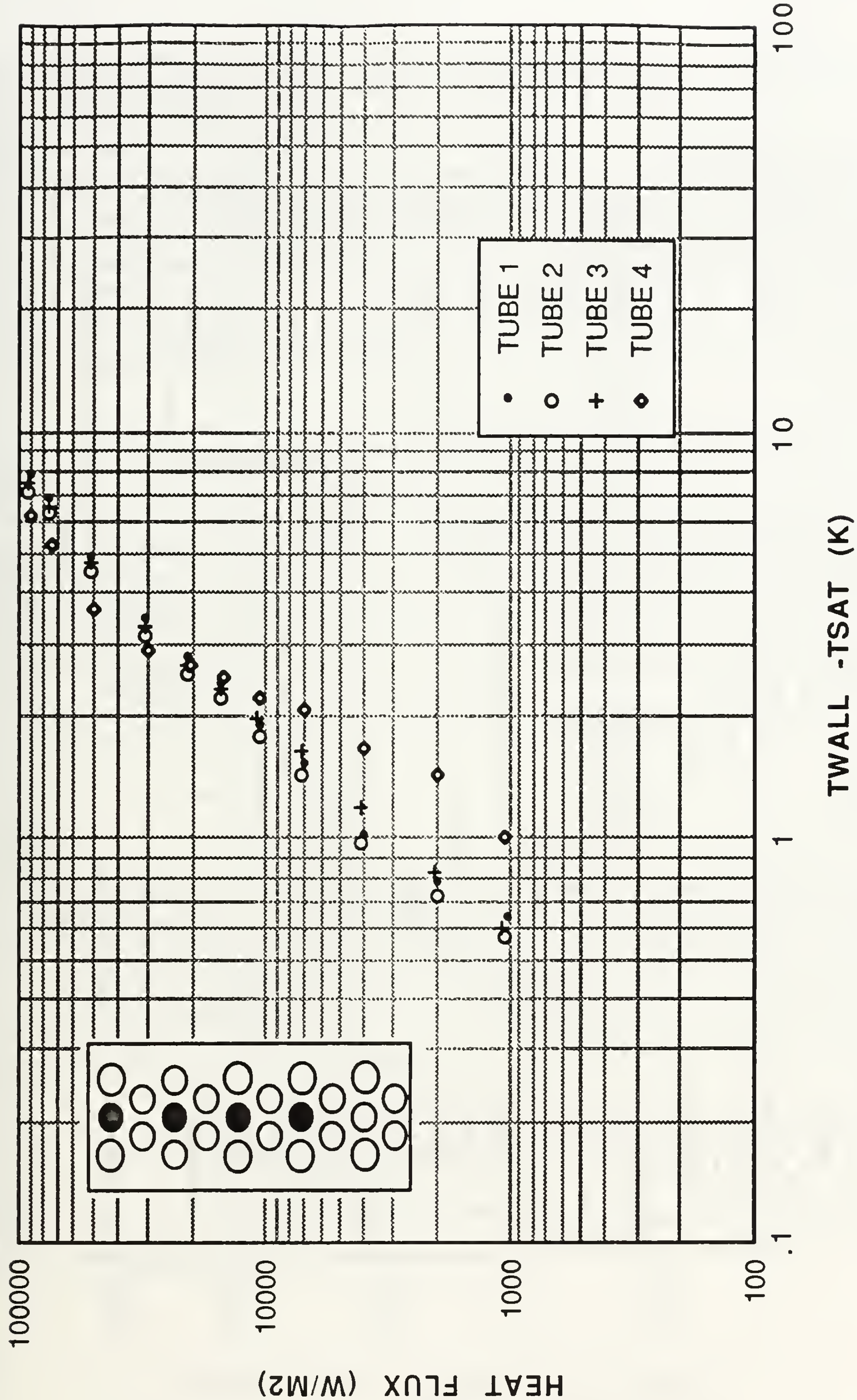

Figure 24. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in Pure R-114

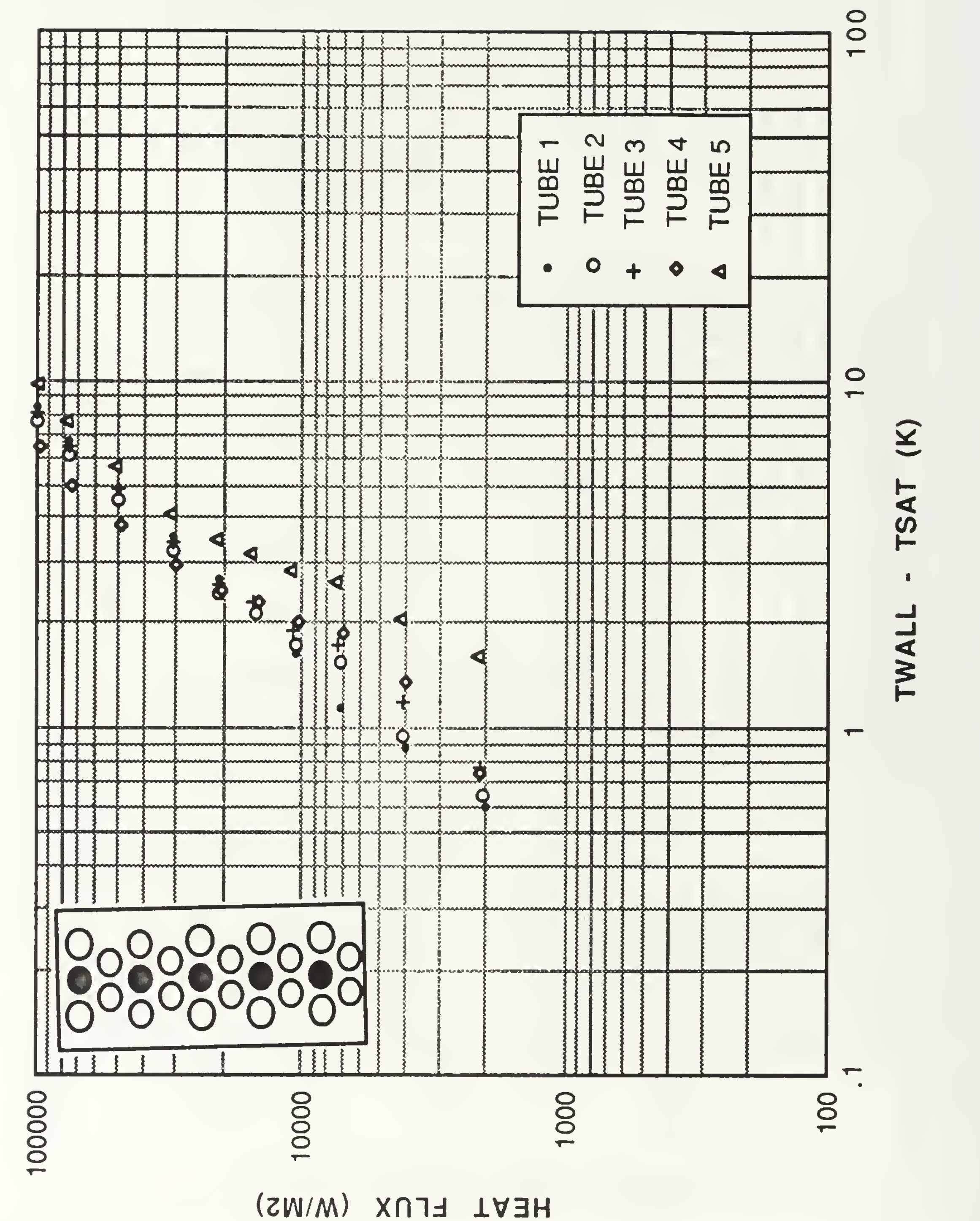

Figure 25. Performance of All Five Tubes for Decreasing Heat Flux in Pure R-114

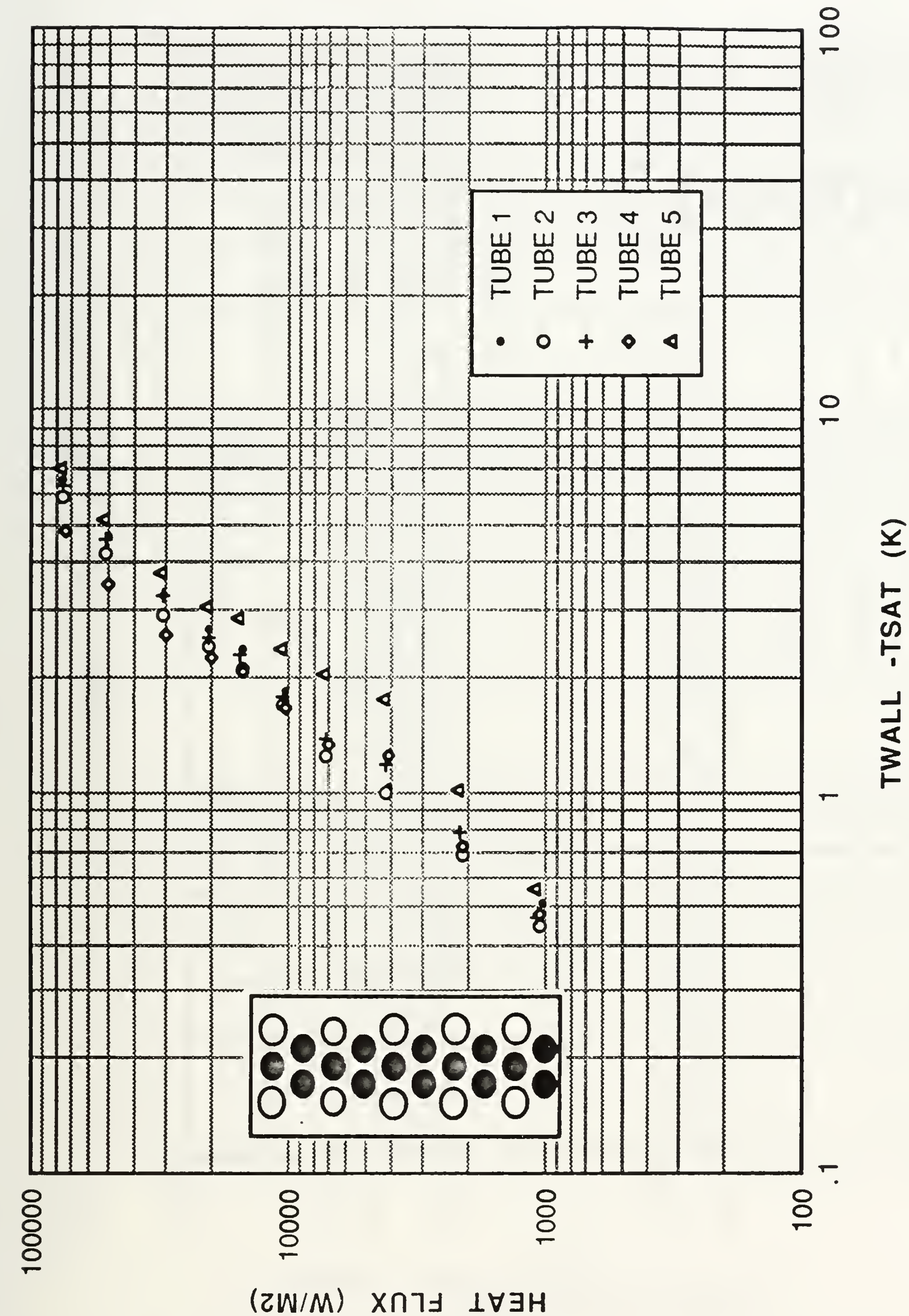

Figure 26. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in Pure R-114

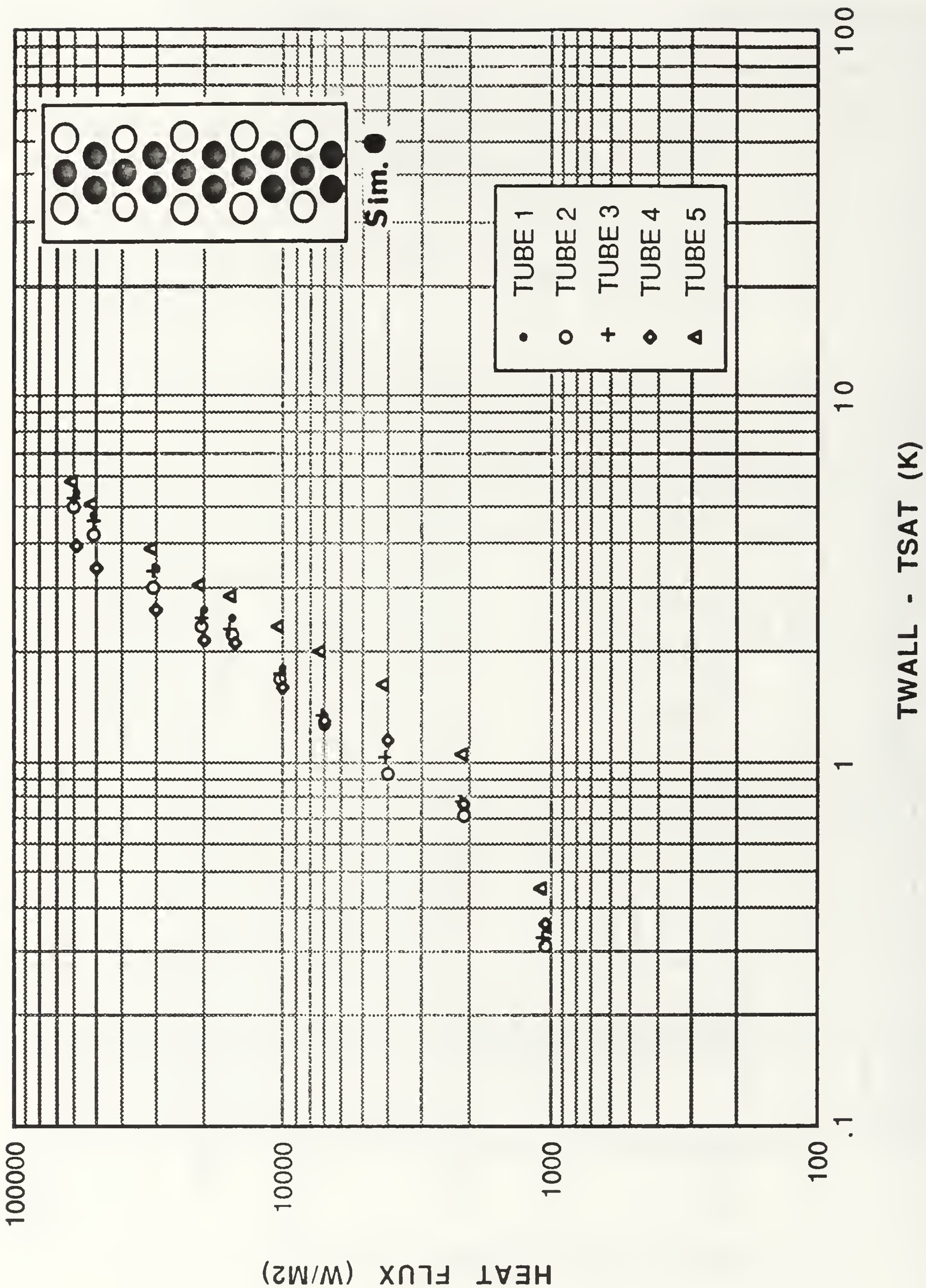

Figure 27. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in Pure R-114

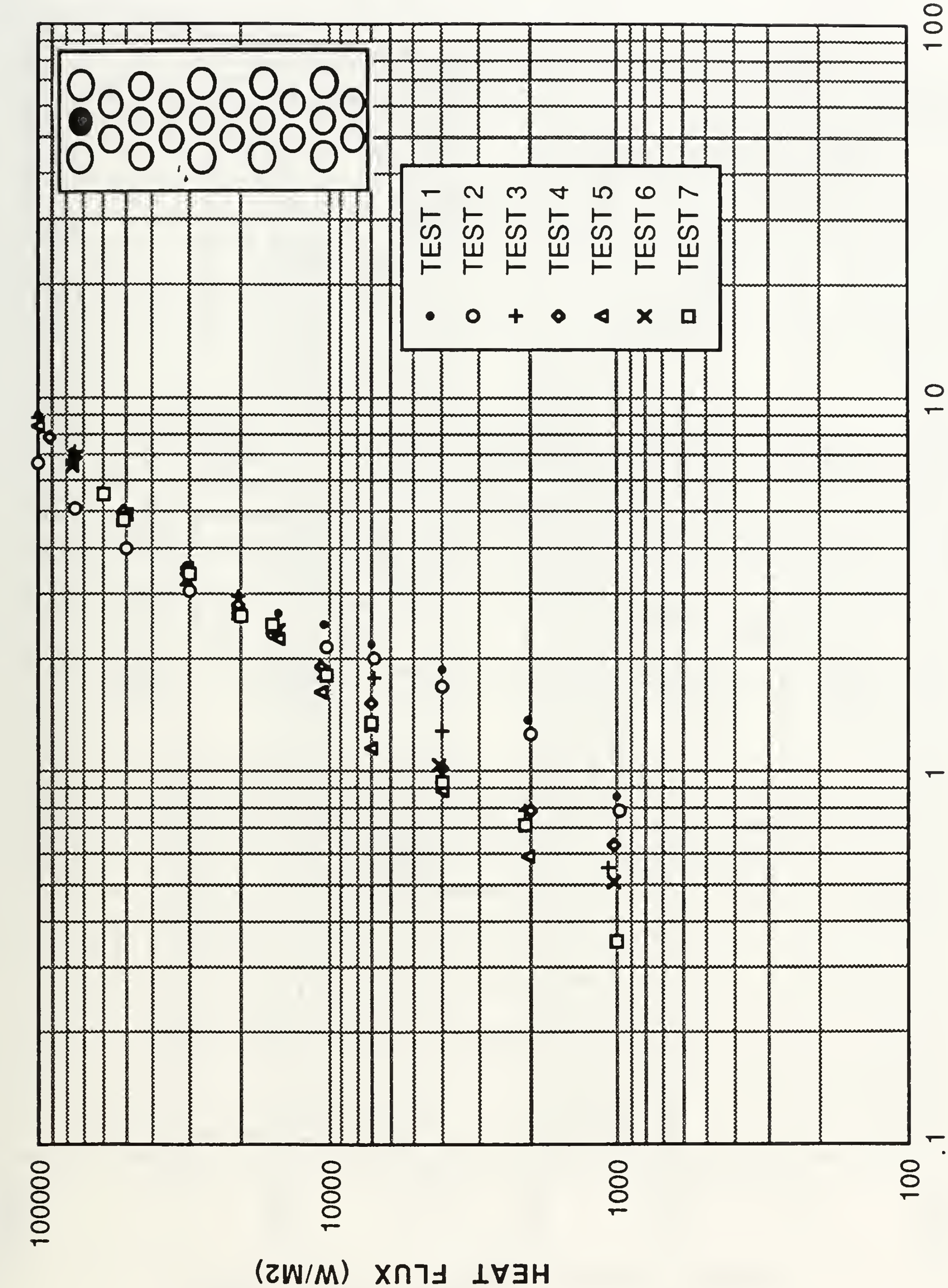

Figure 28. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in Pure R-114

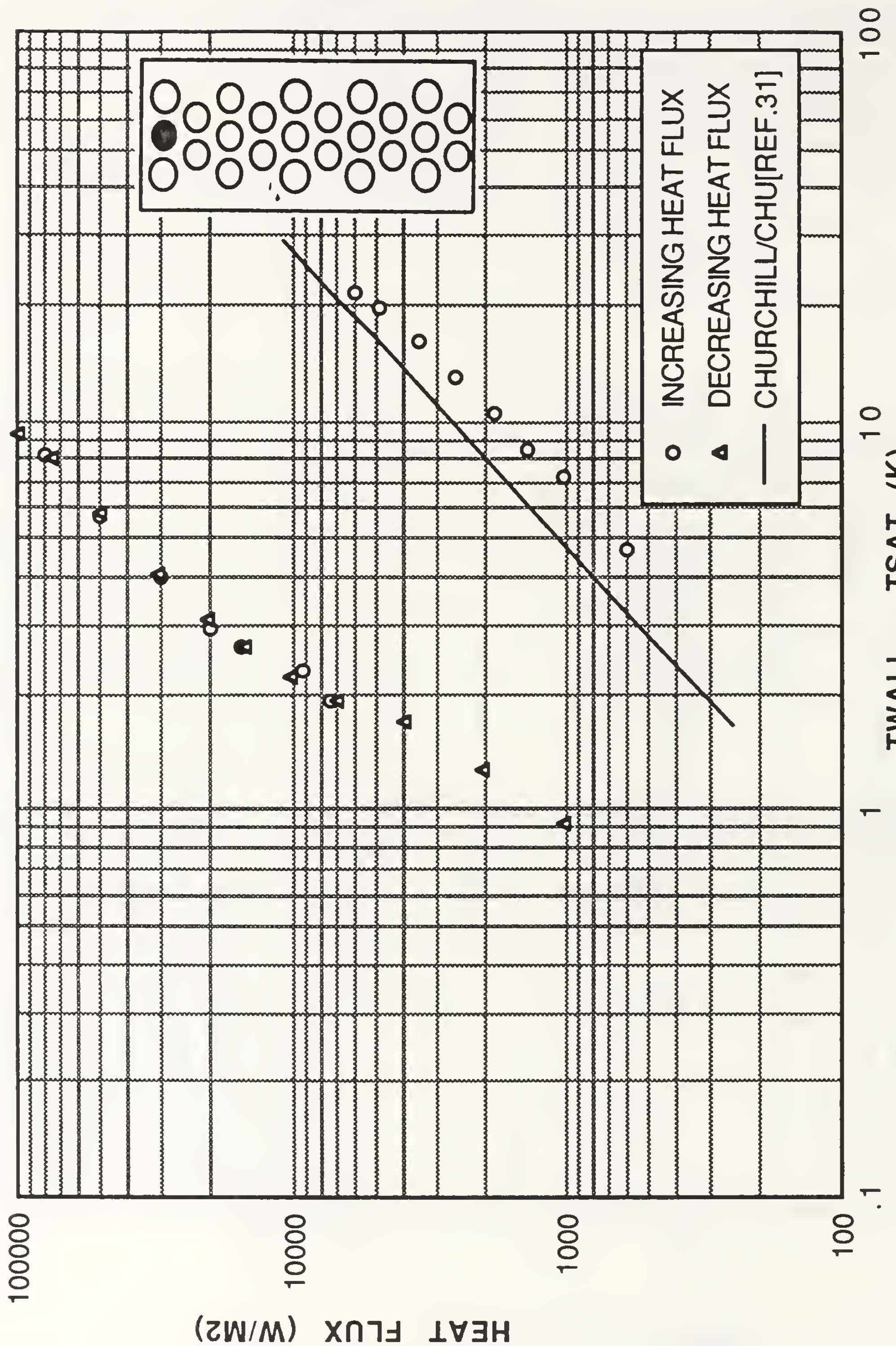

Figure 29. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 1% Oil

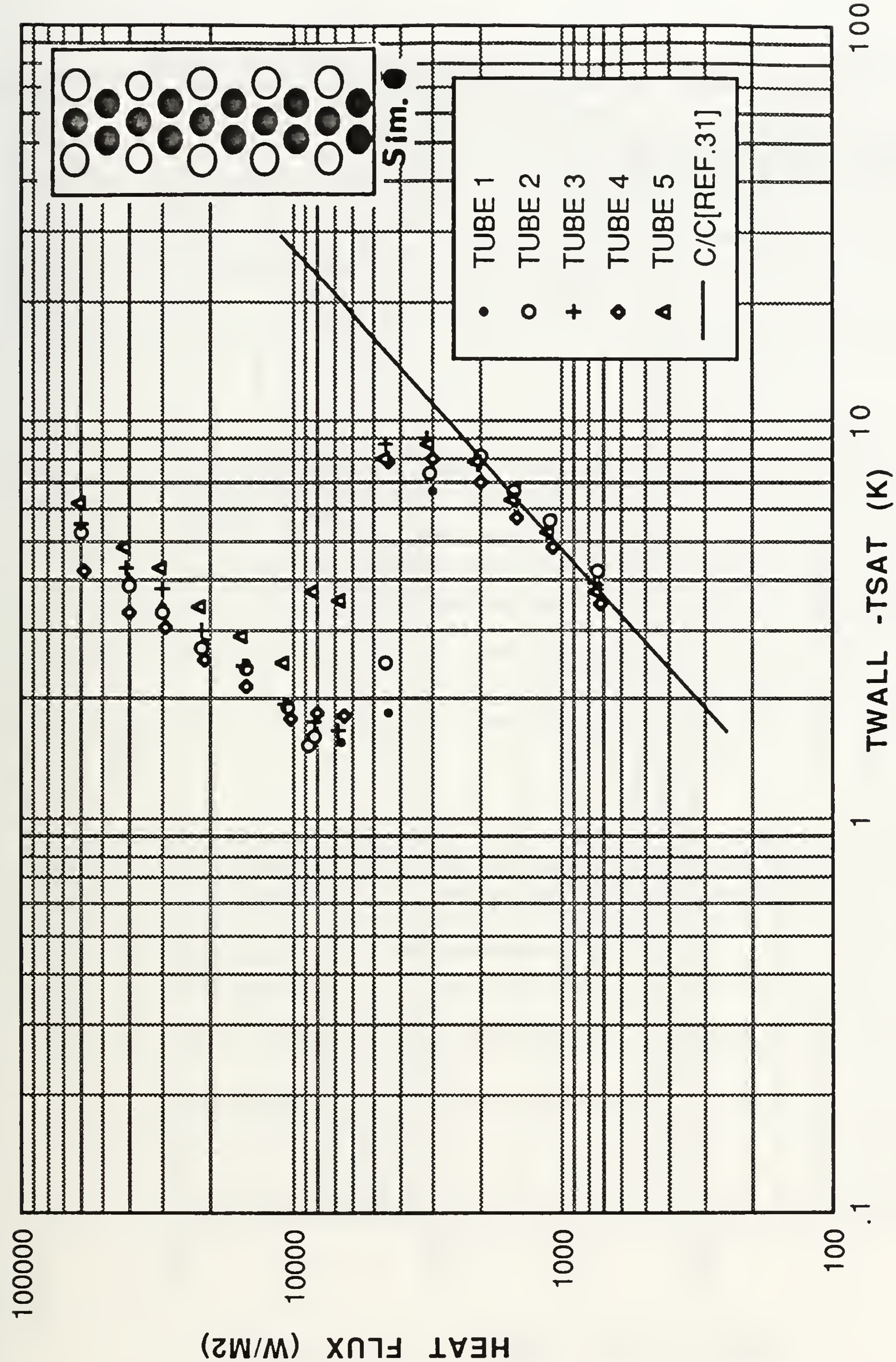

Figure 30. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 1% Oil

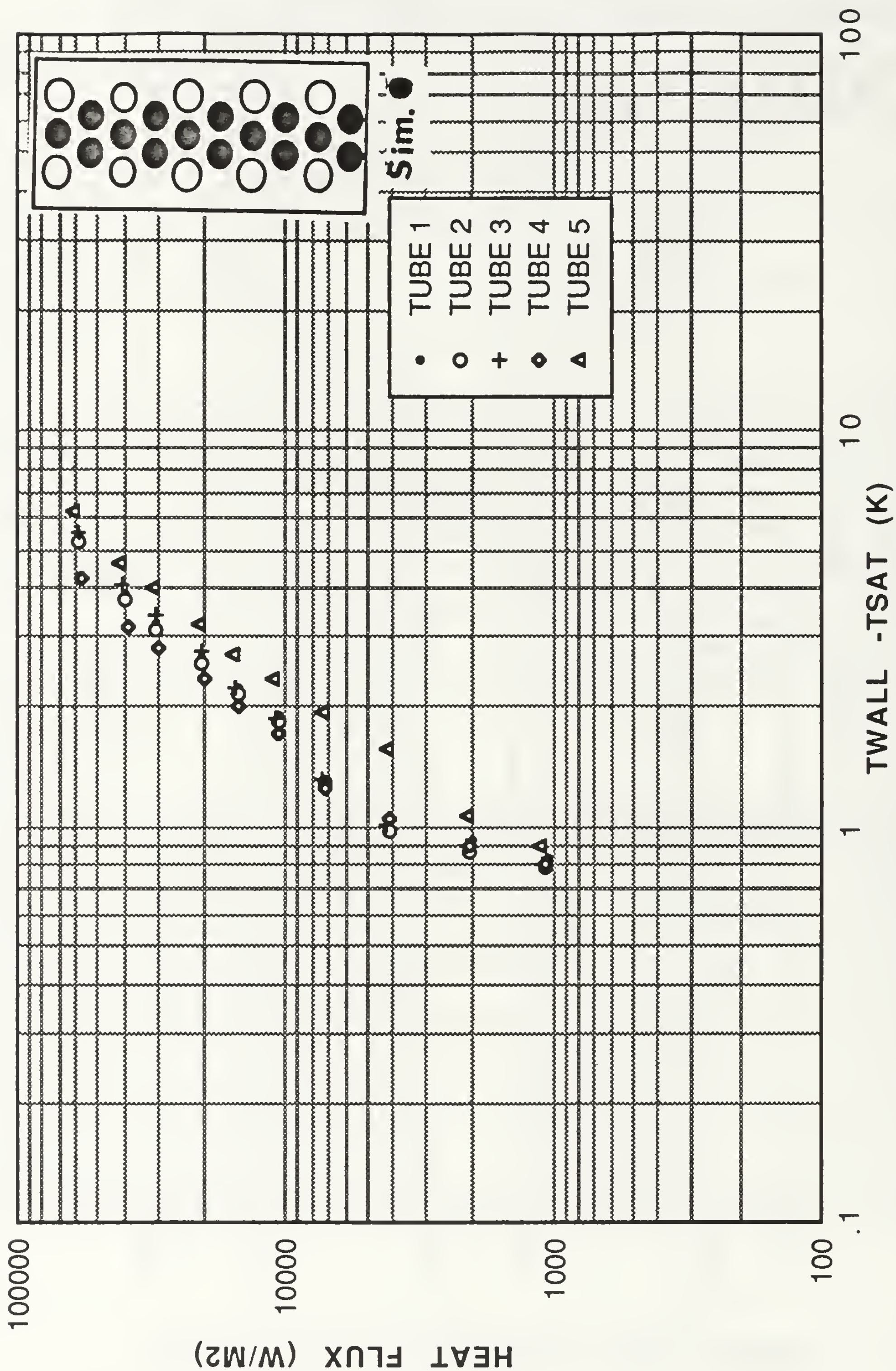

Figure 31. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 1% Oil

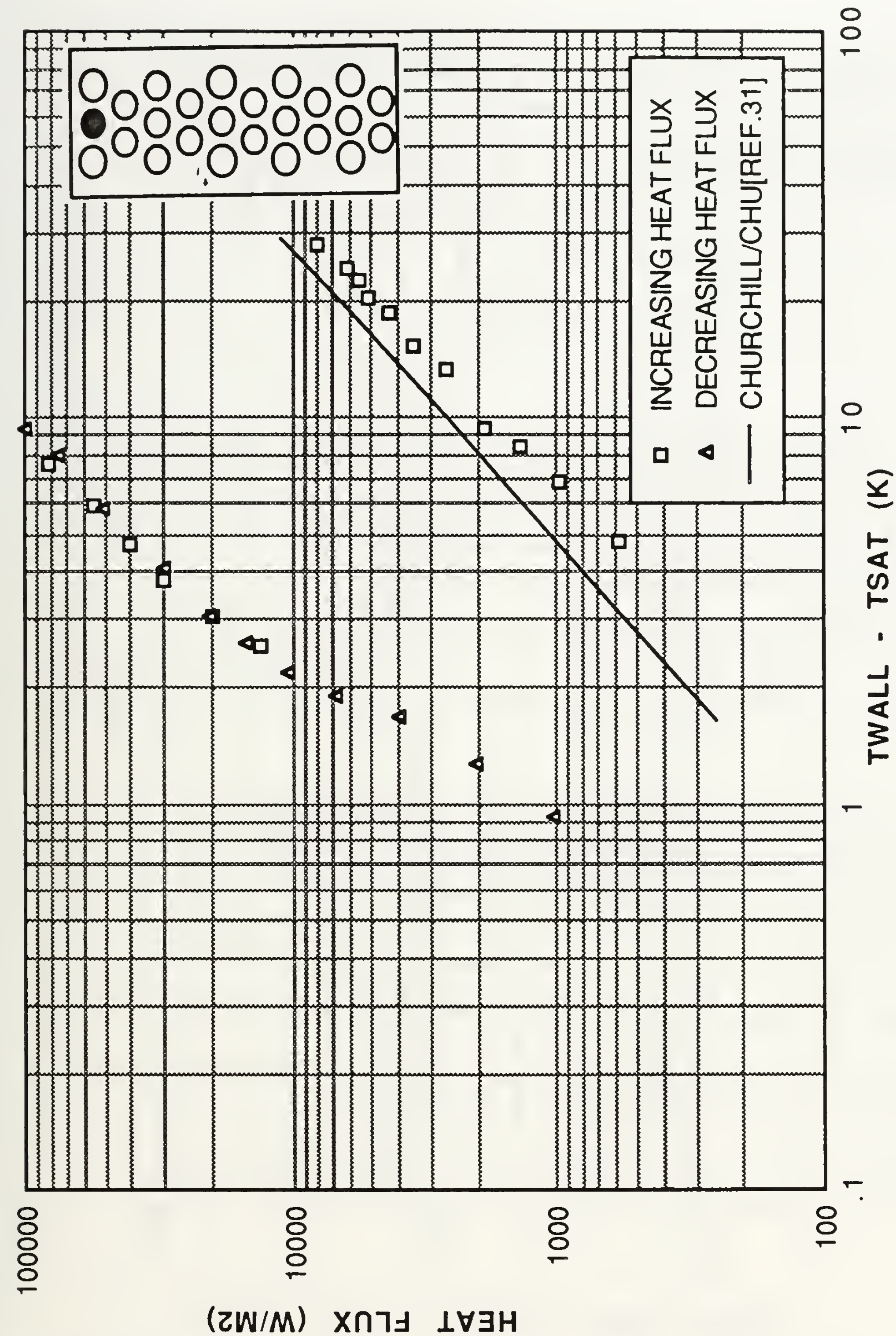

Figure 32. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 2% Oil

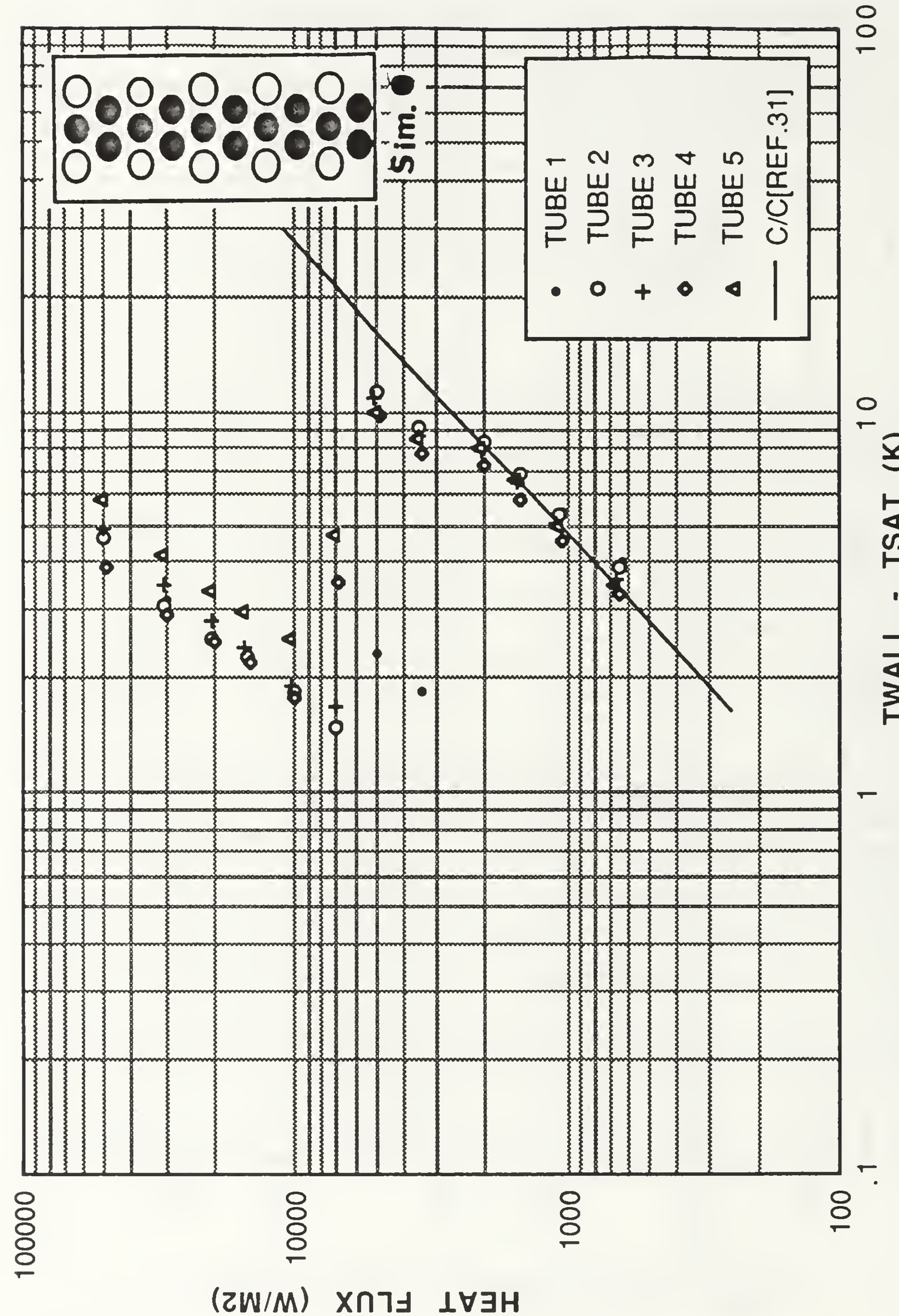

Figure 33. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 2% Oil

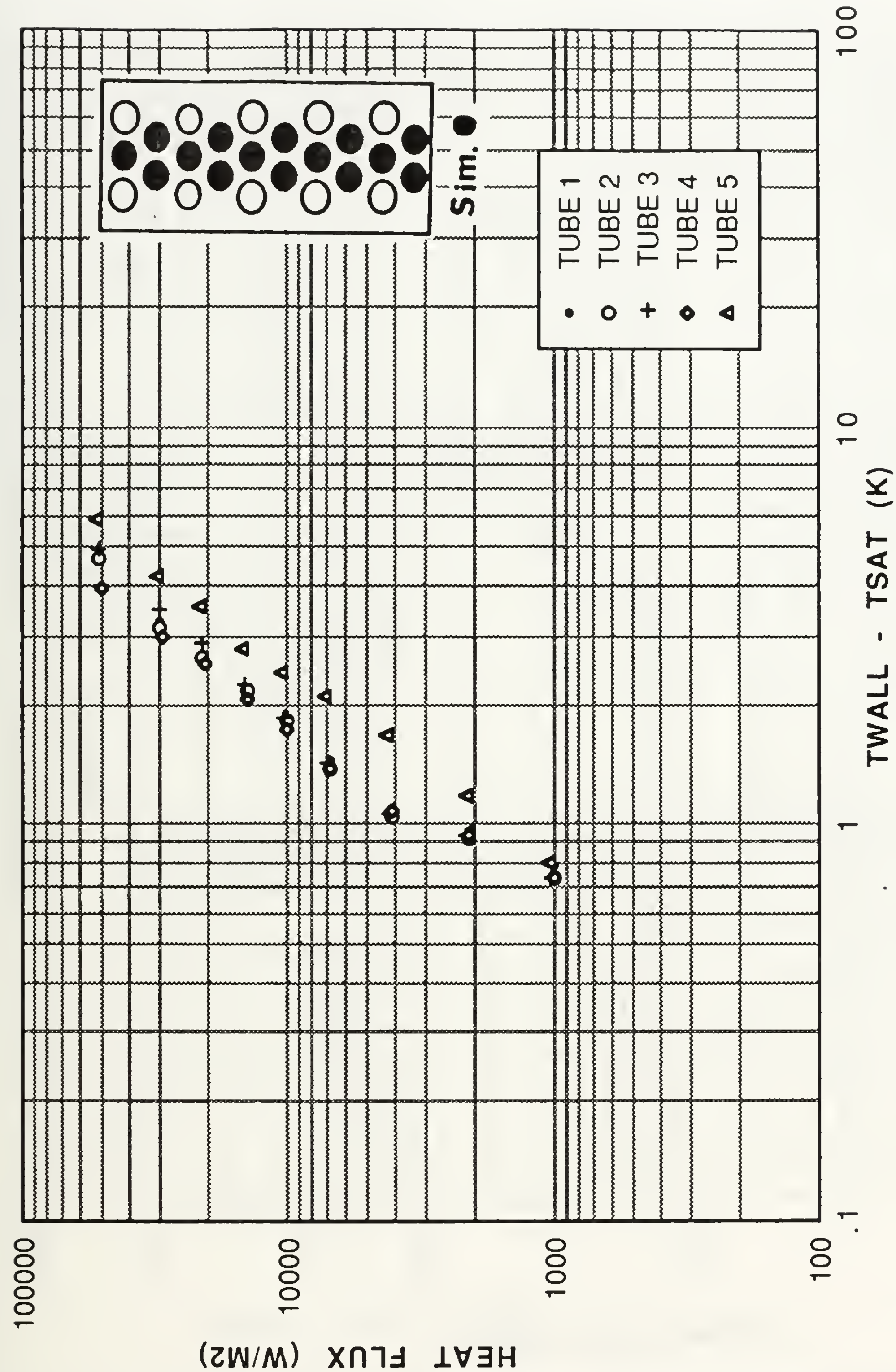

Figure 34. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 2% Oil

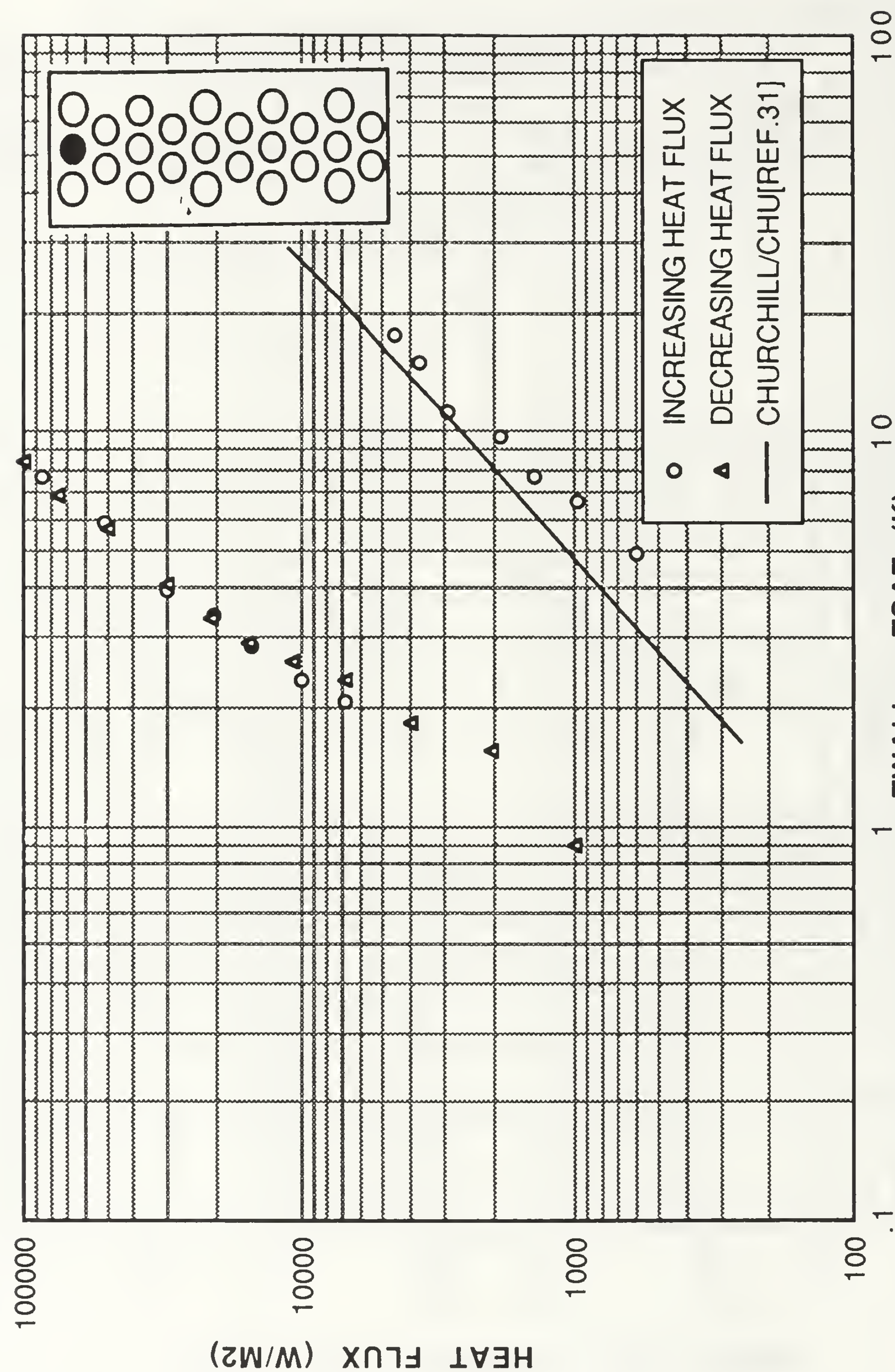

Figure 35. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 3% Oil

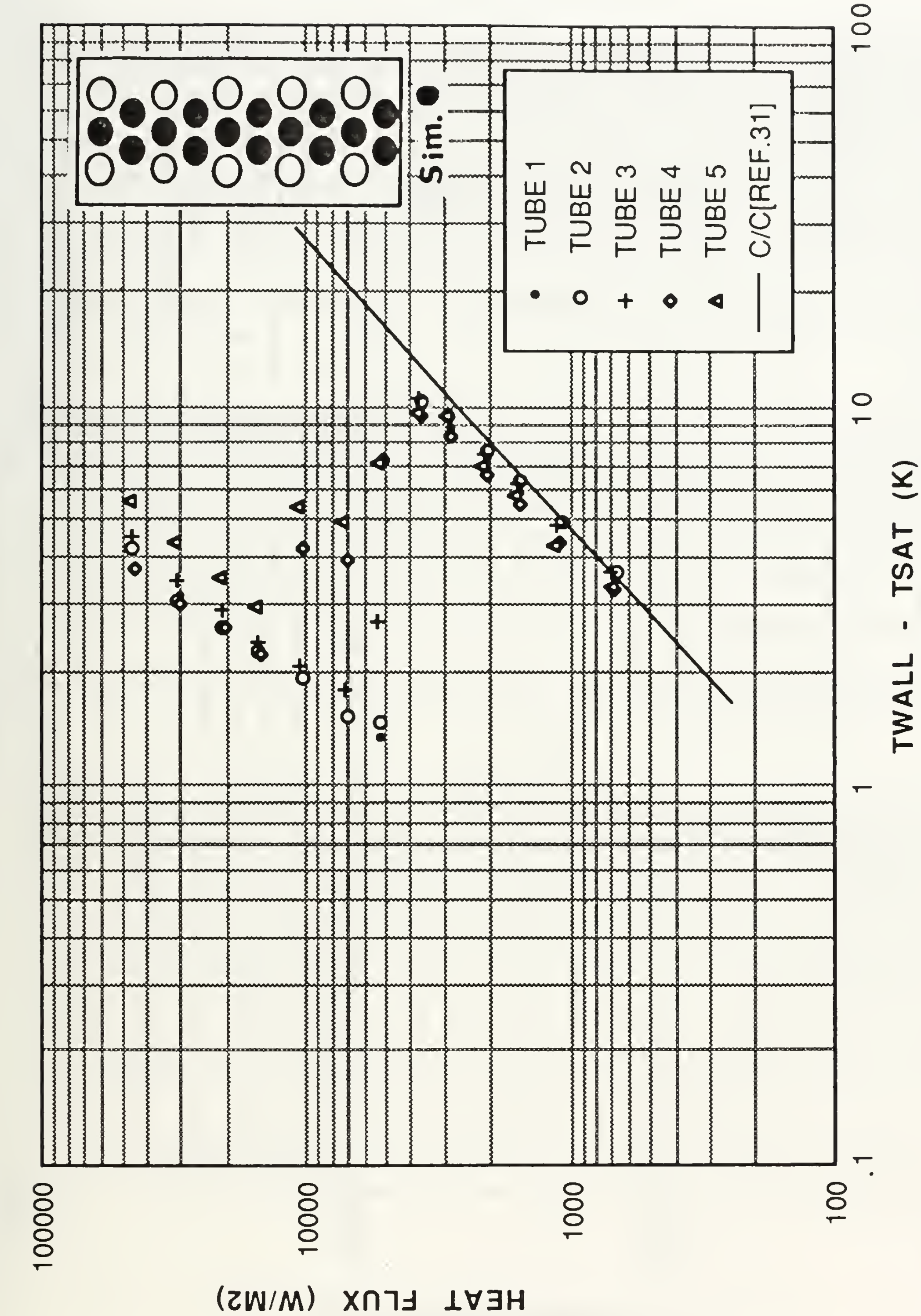

Figure 36. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 3% Oil

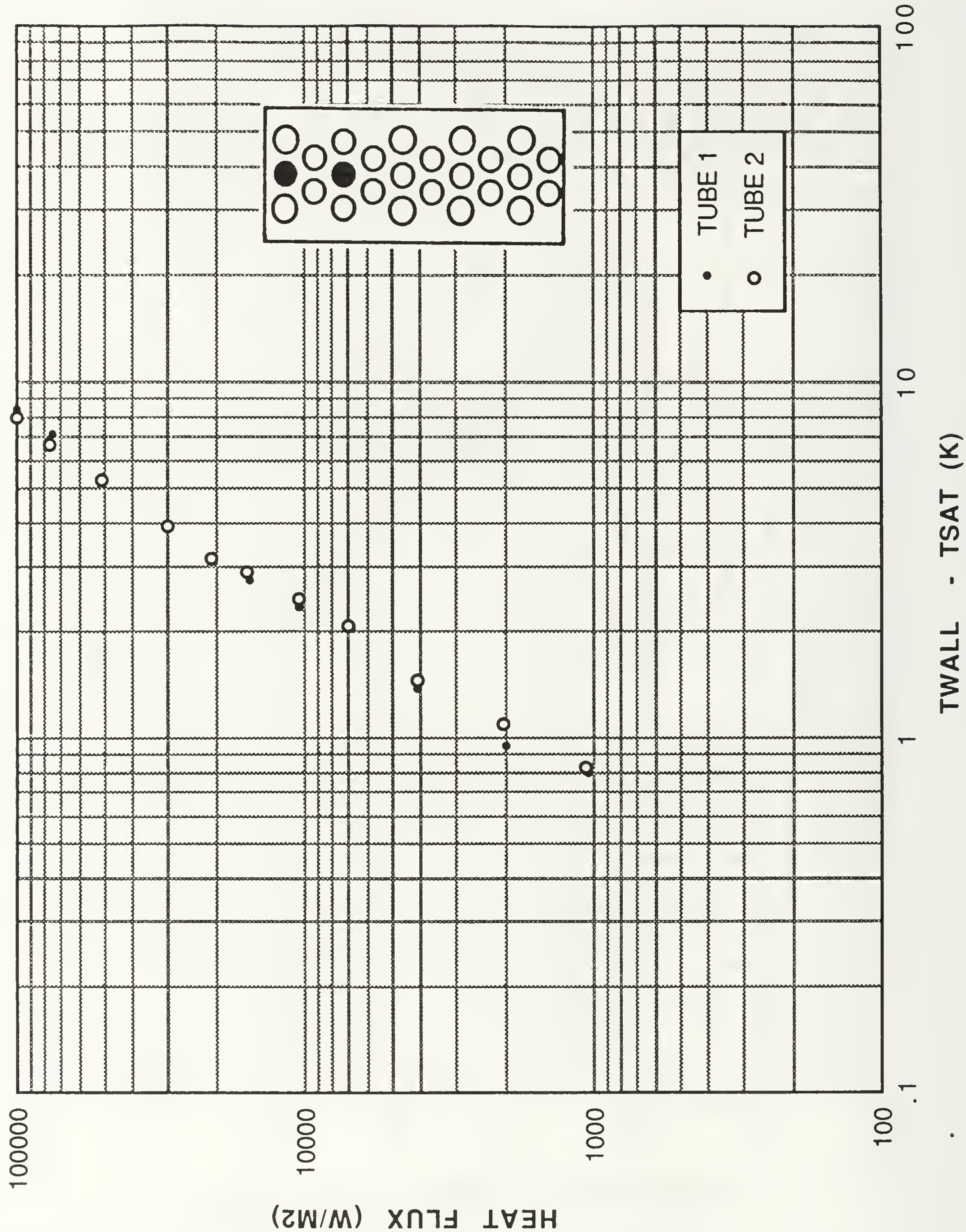

Figure 37. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 3% Oil

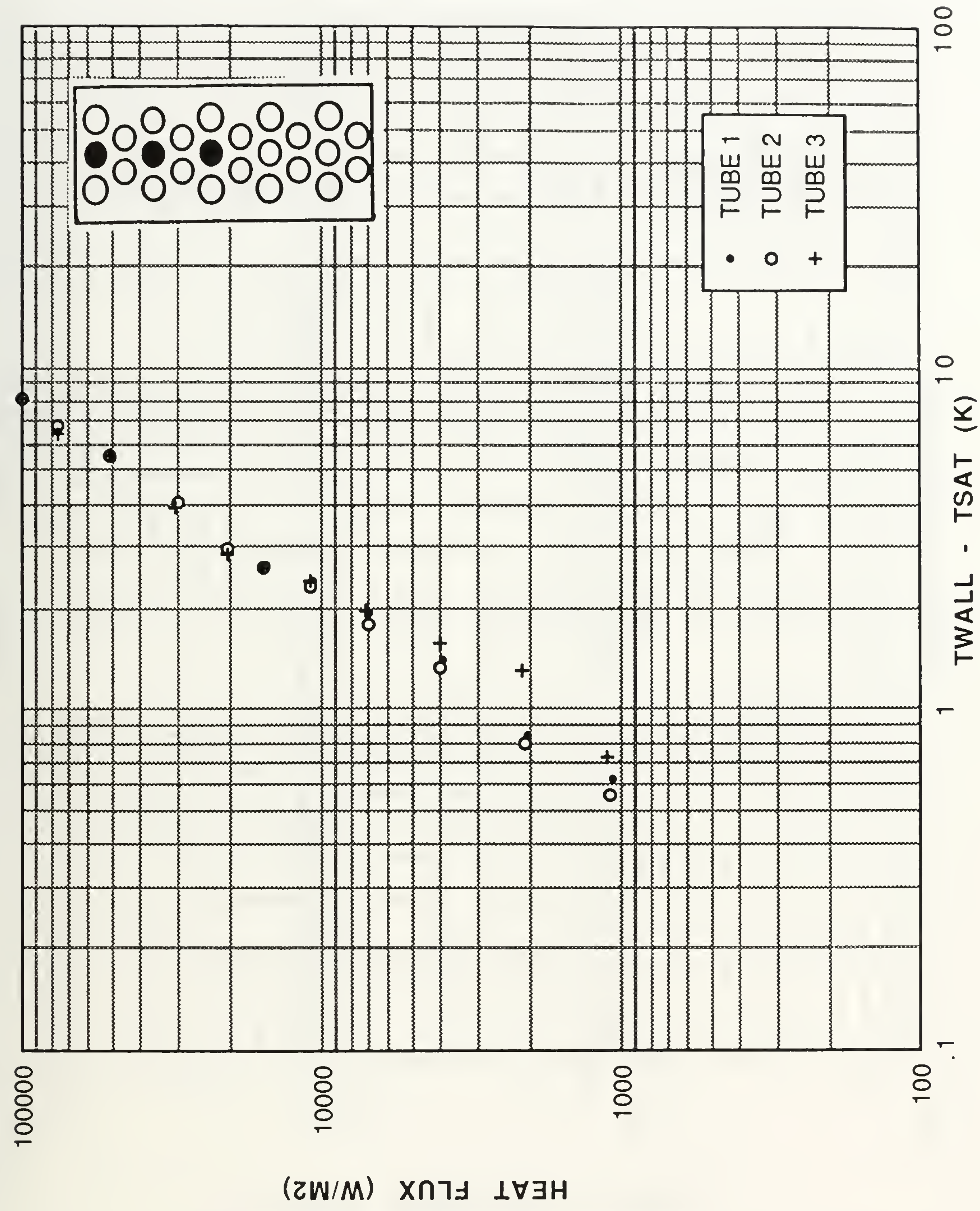

Figure 38. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 3% Oil

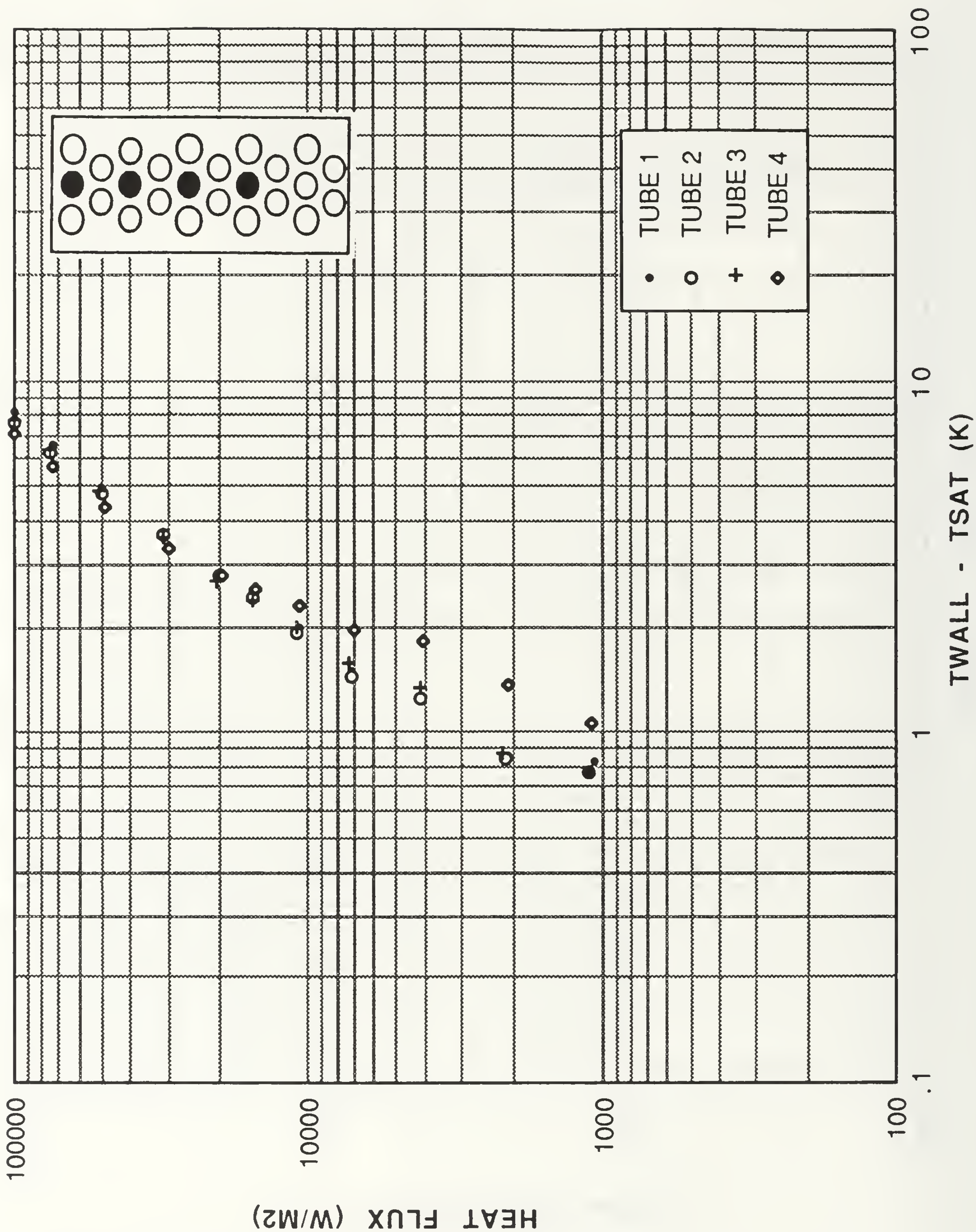

Figure 39. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 3% Oil

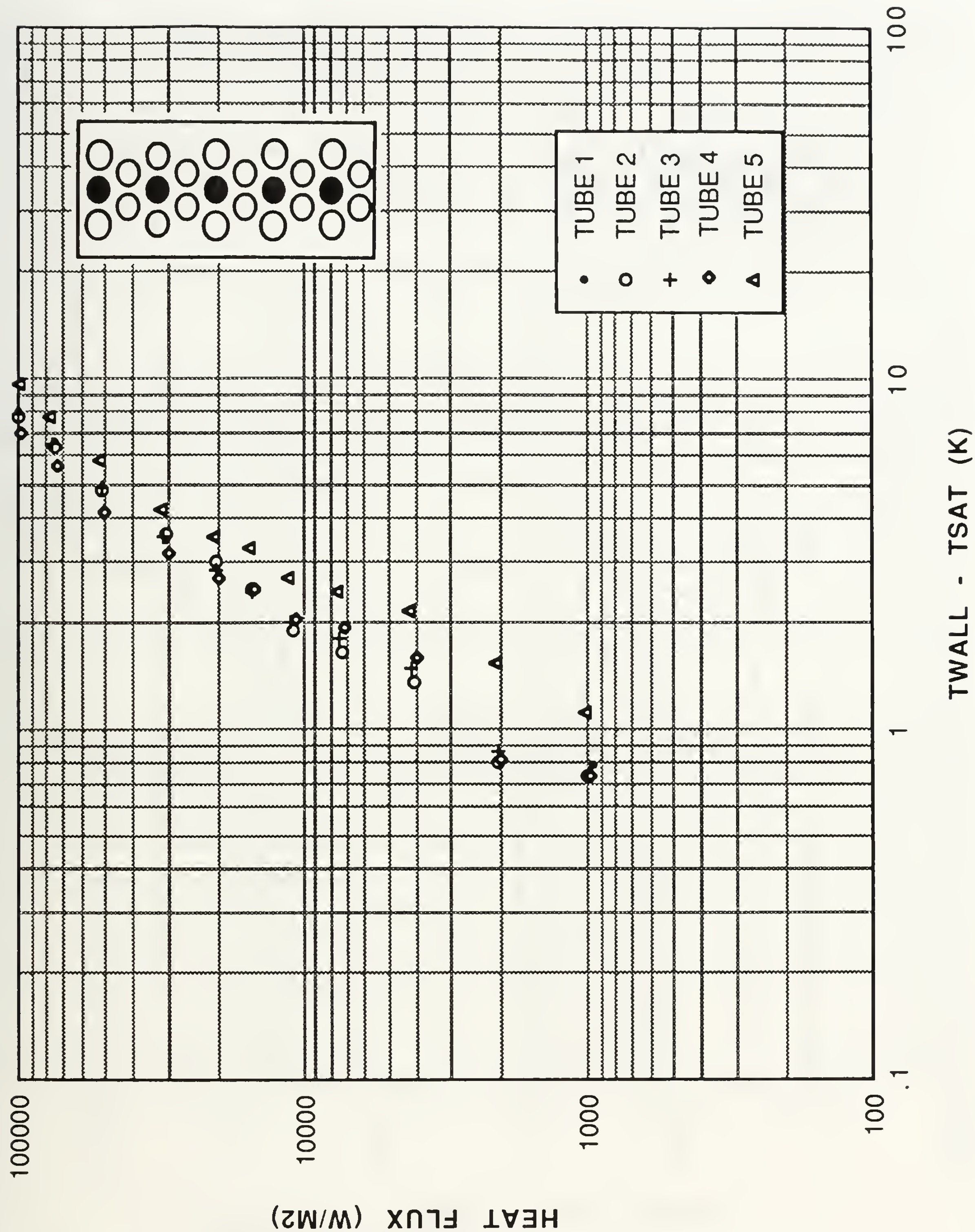

Figure 40. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 3% Oil

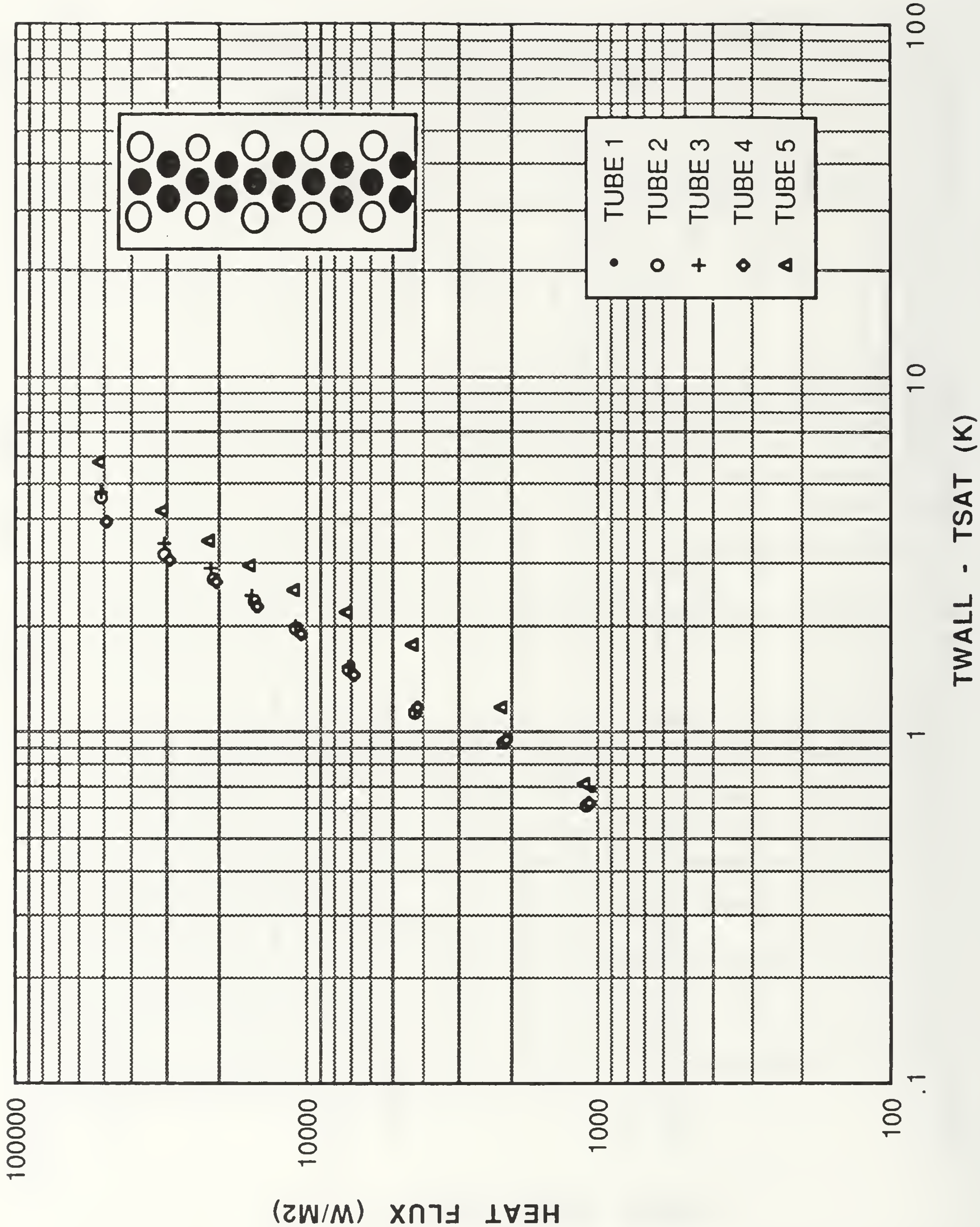

Figure 41. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 3% Oil

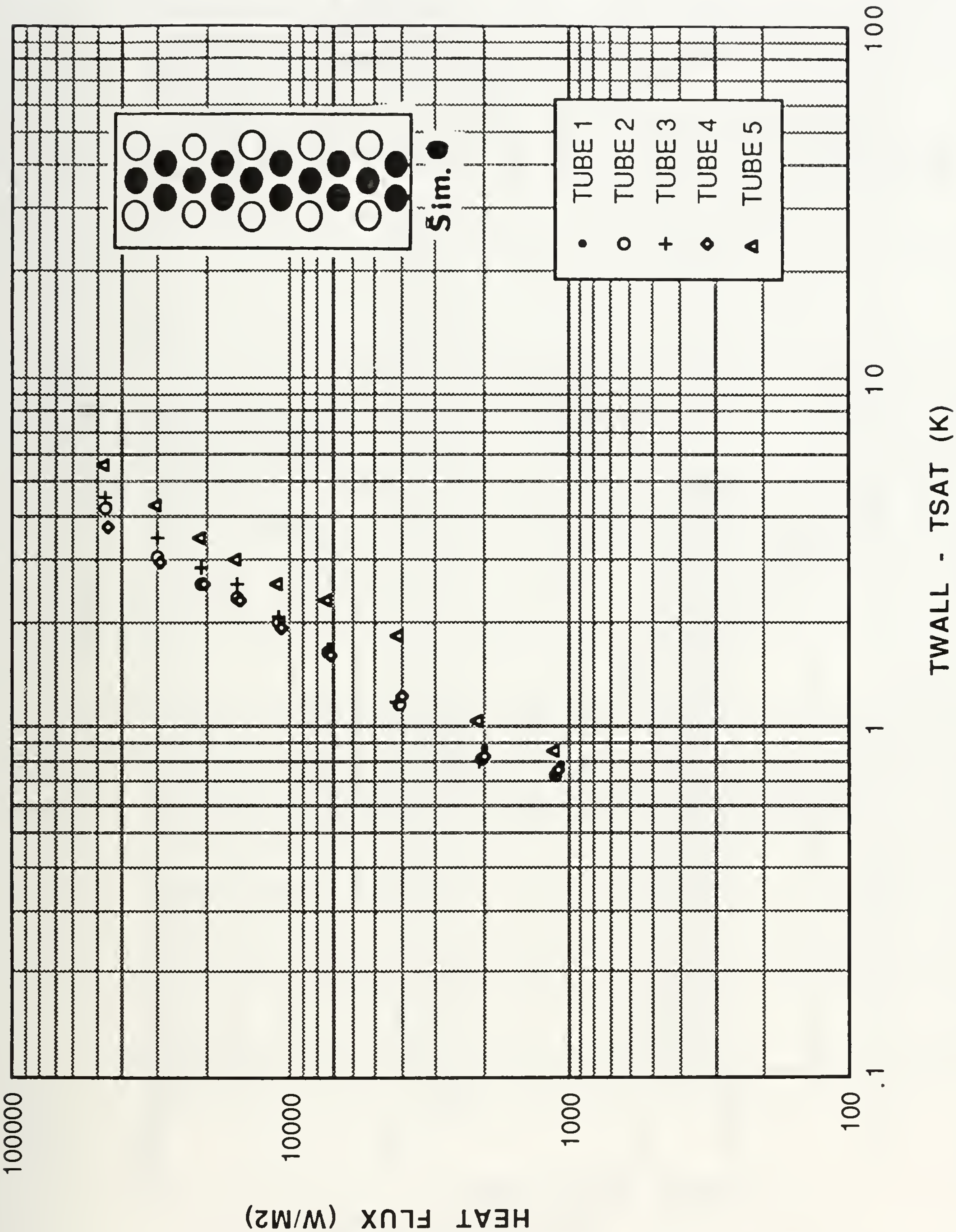

Figure 42. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 3% Oil

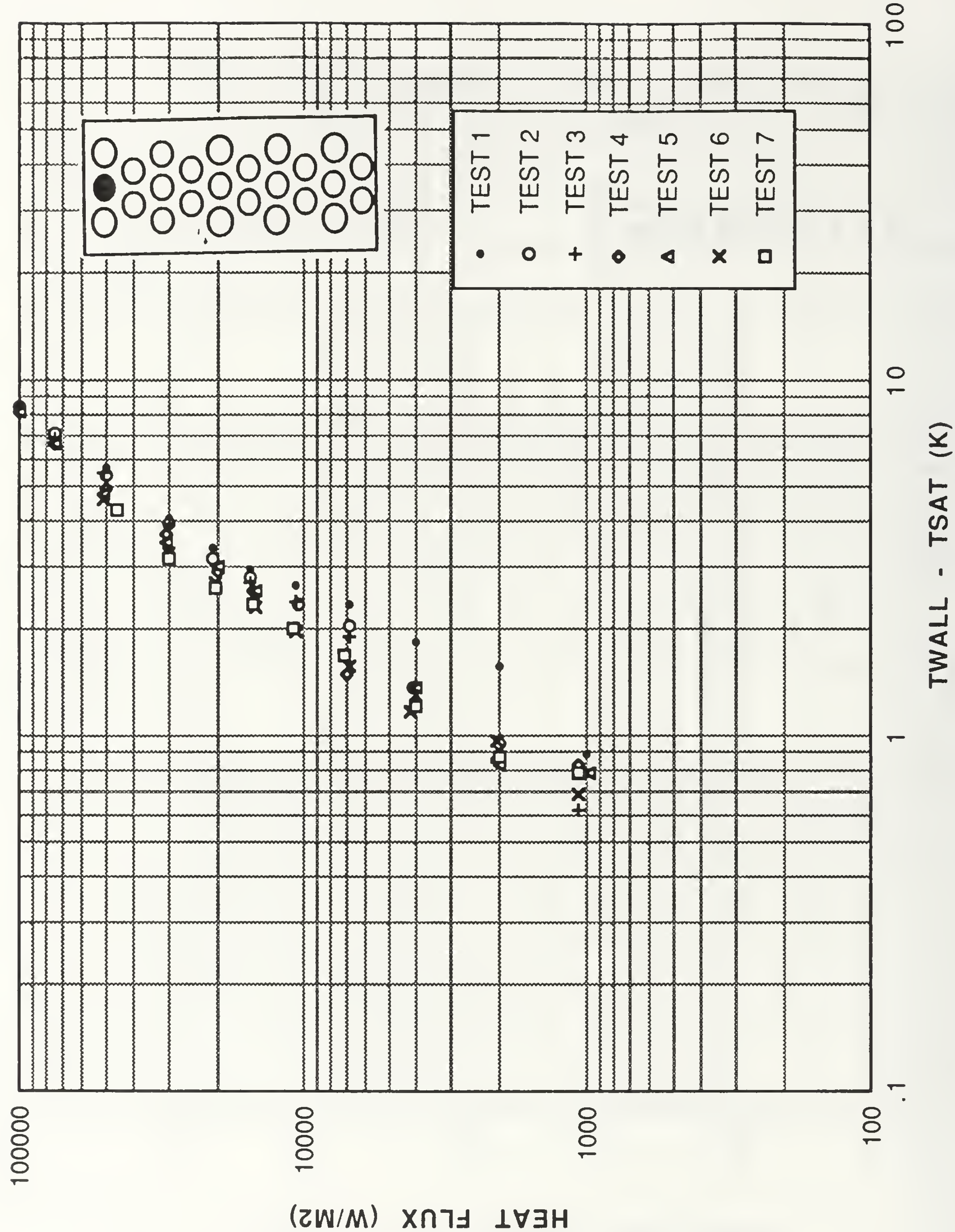

Figure 43. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in R-114 with 3% Oil

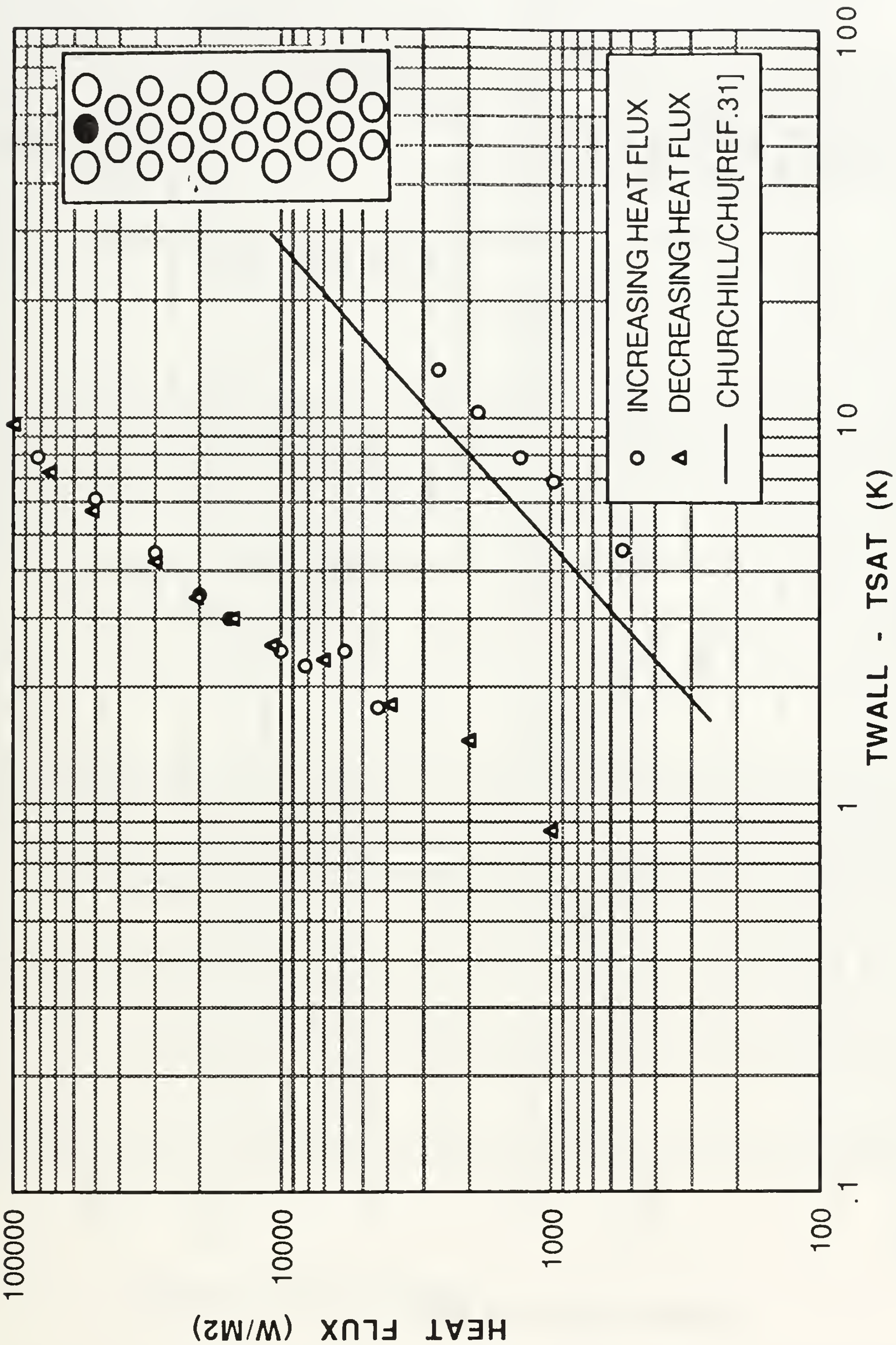

Figure 44. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 6% Oil

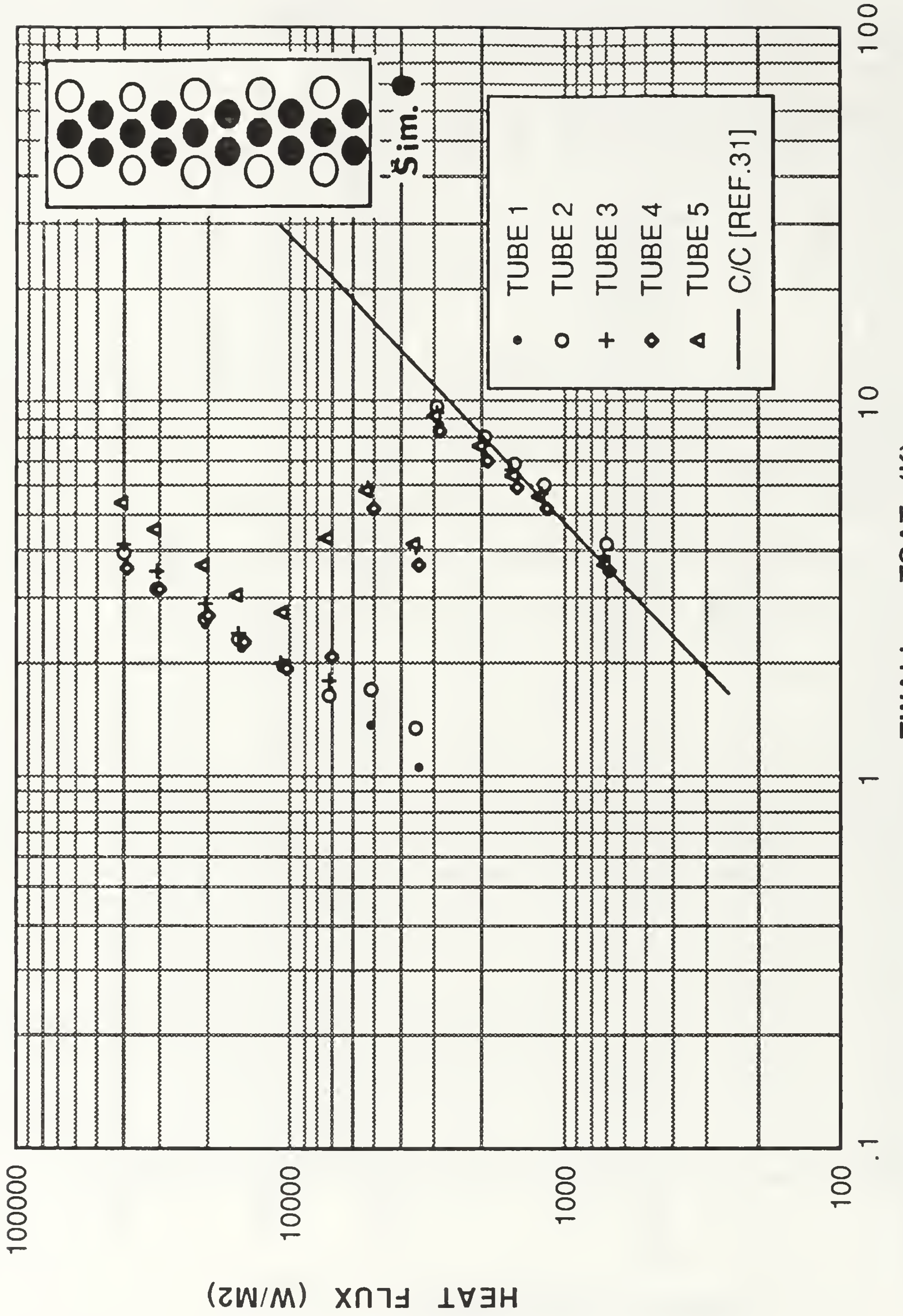

Figure 45. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 6% Oil

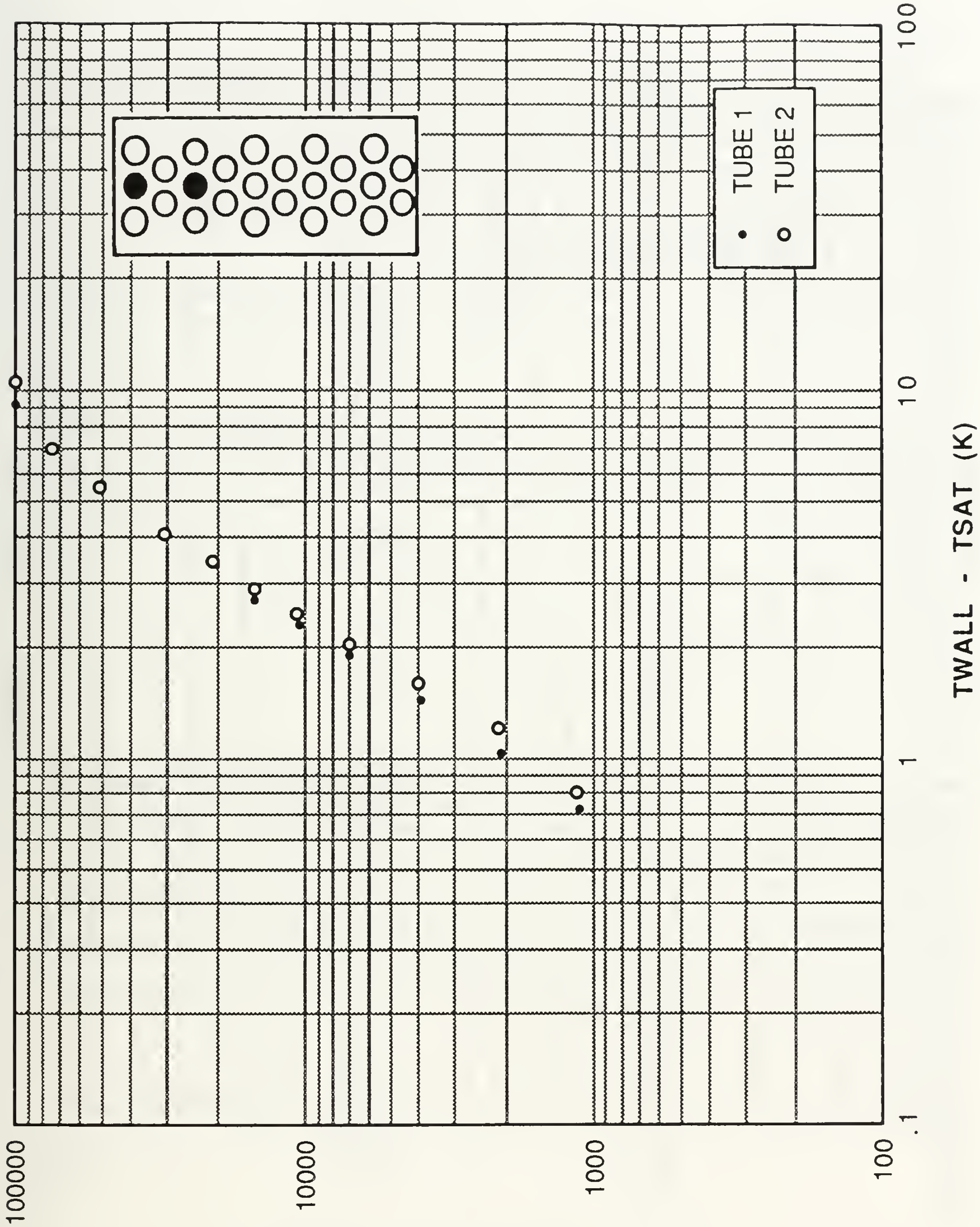

Figure 46. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 6% Oil

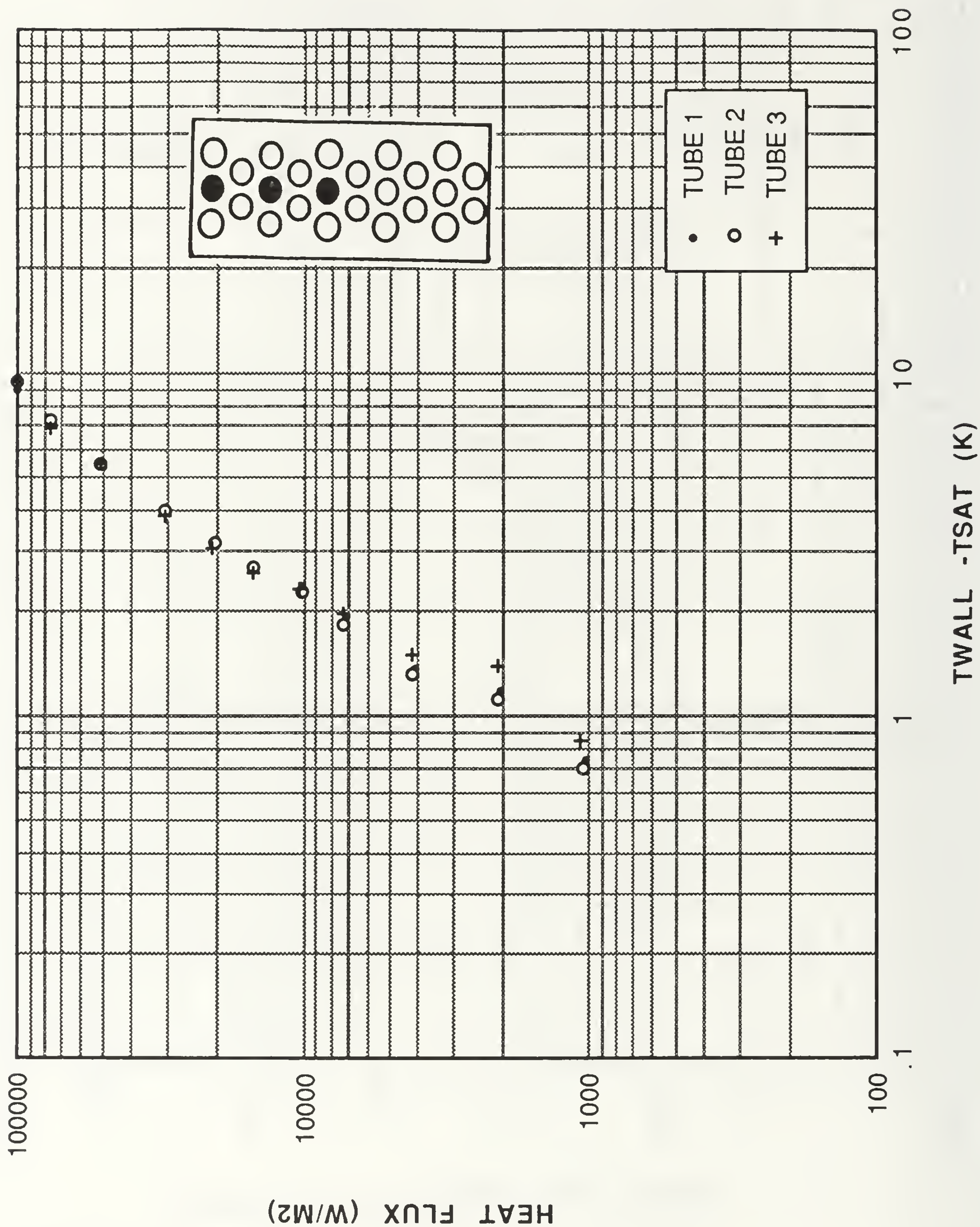

Figure 47. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 6% Oil

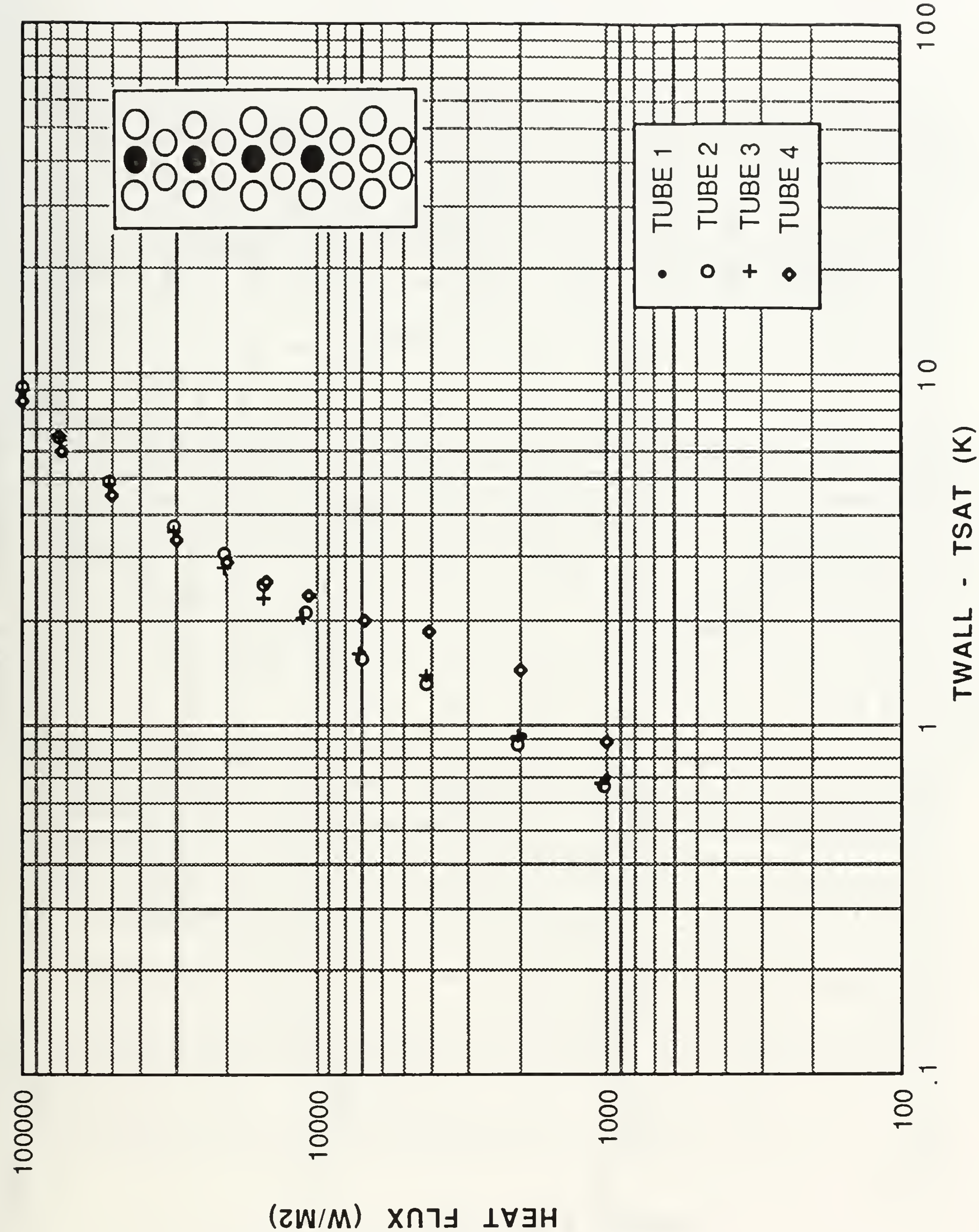

Figure 48. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 6% Oil

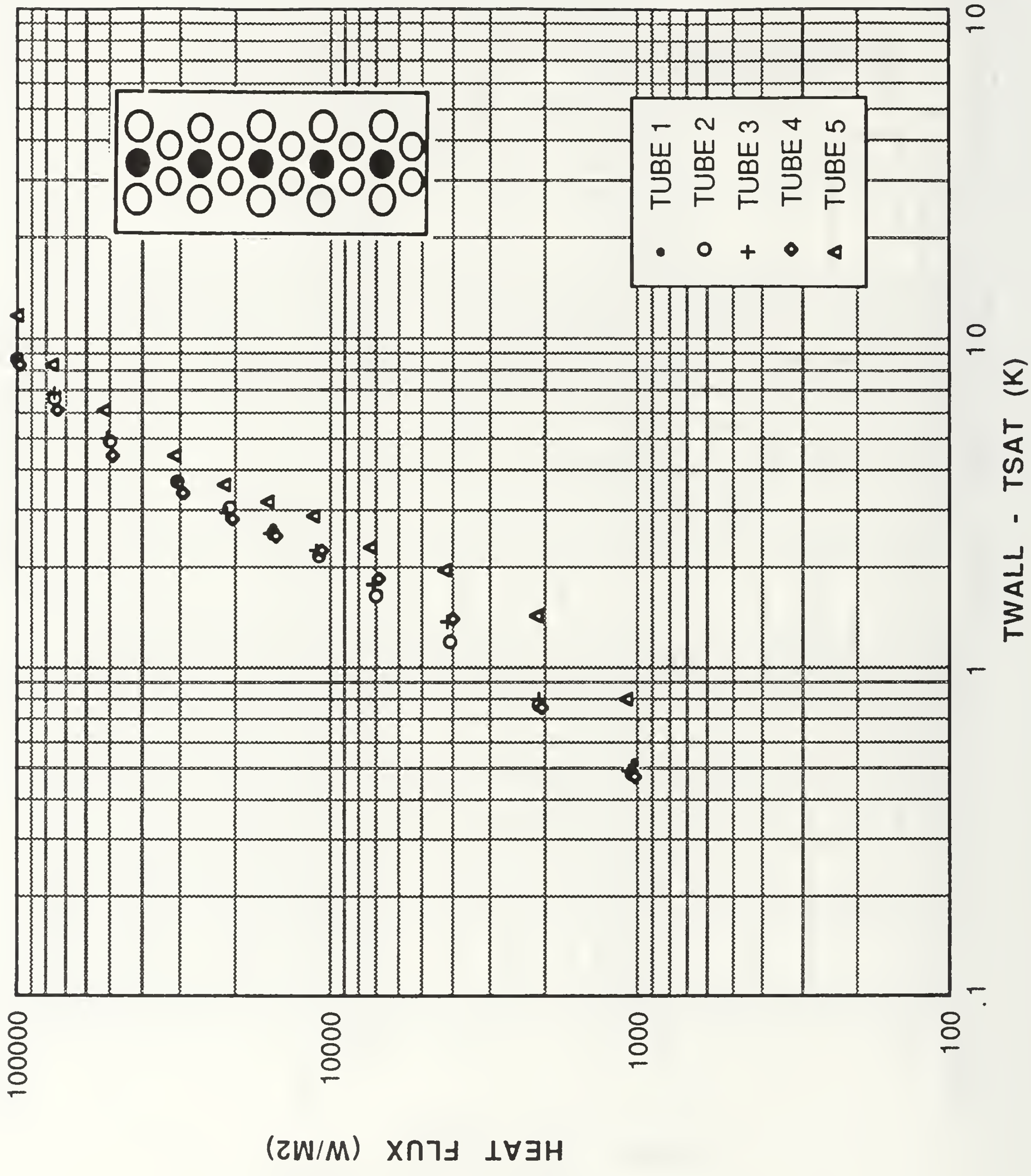

Figure 49. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 6% Oil

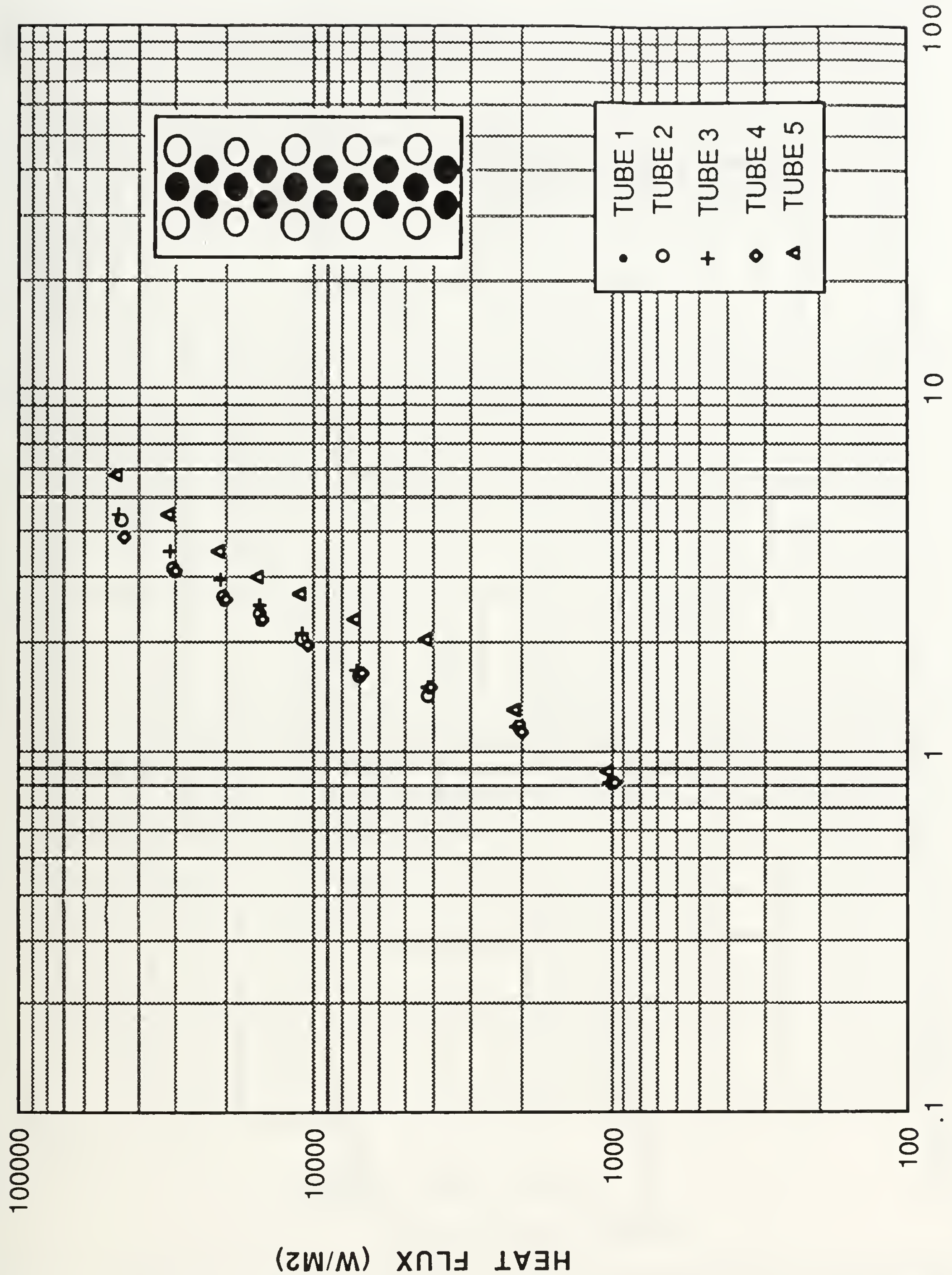

Figure 50. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 6% Oil

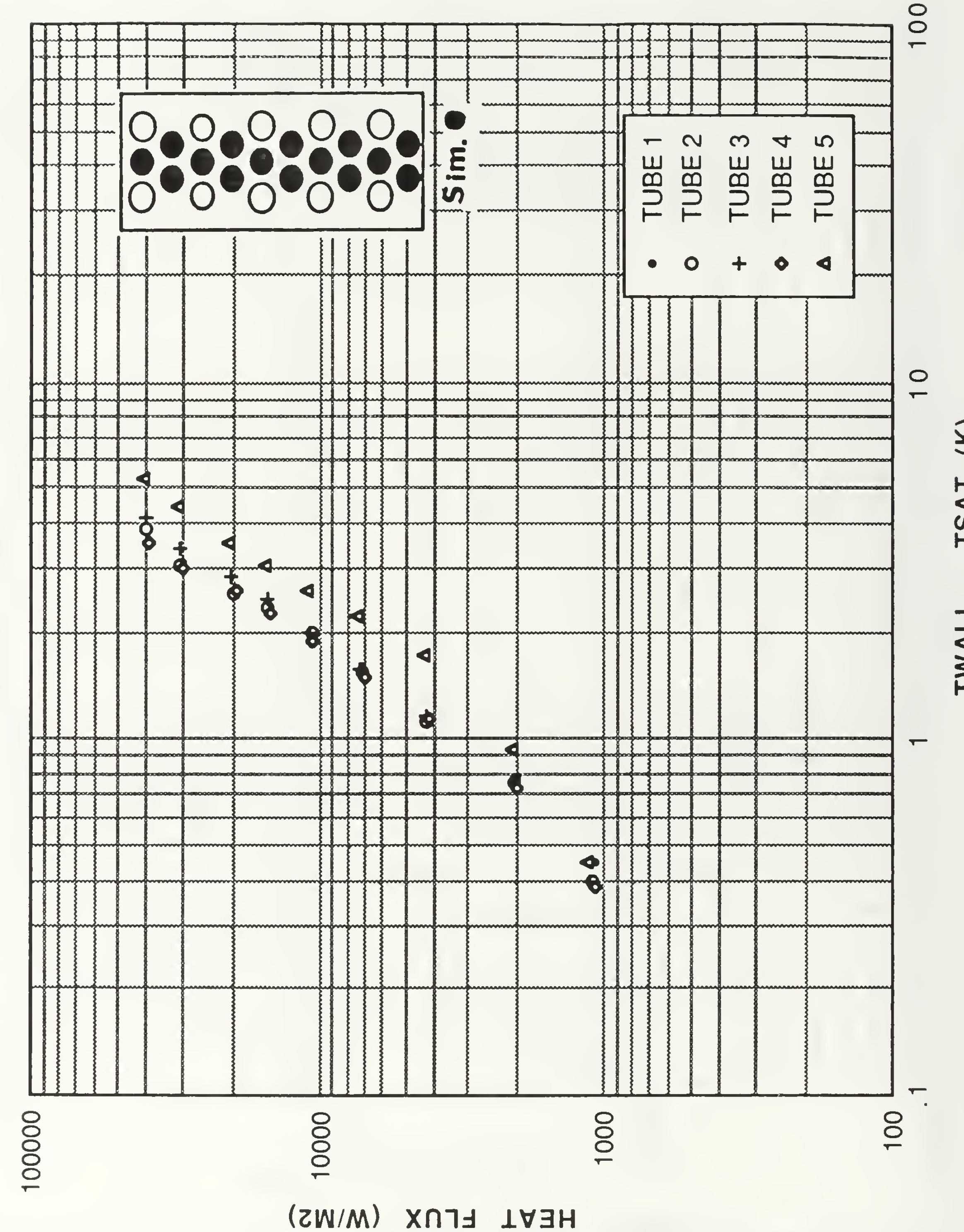

Figure 51. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 6% Oil

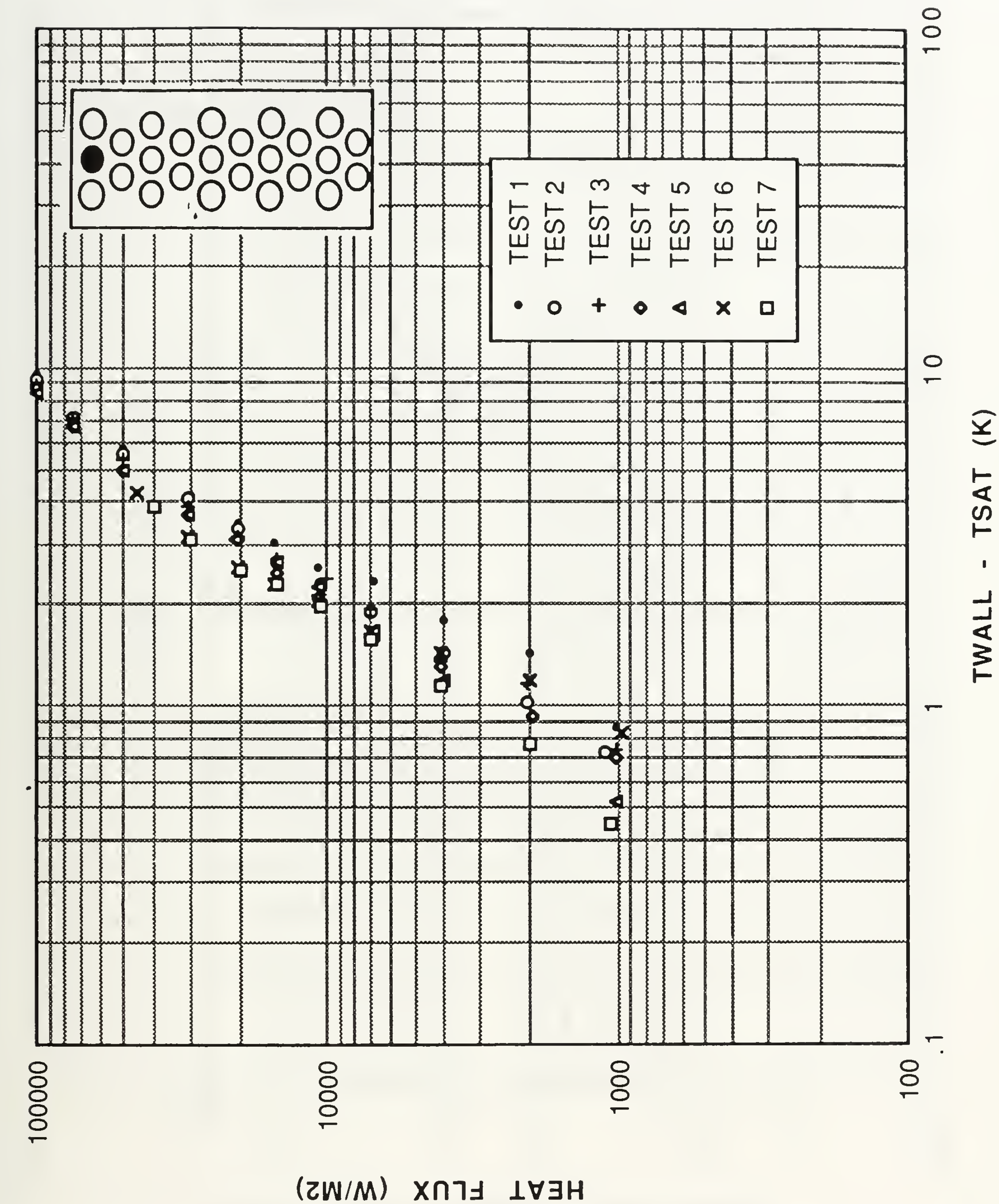

Figure 52. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in R-114 with 6% Oil

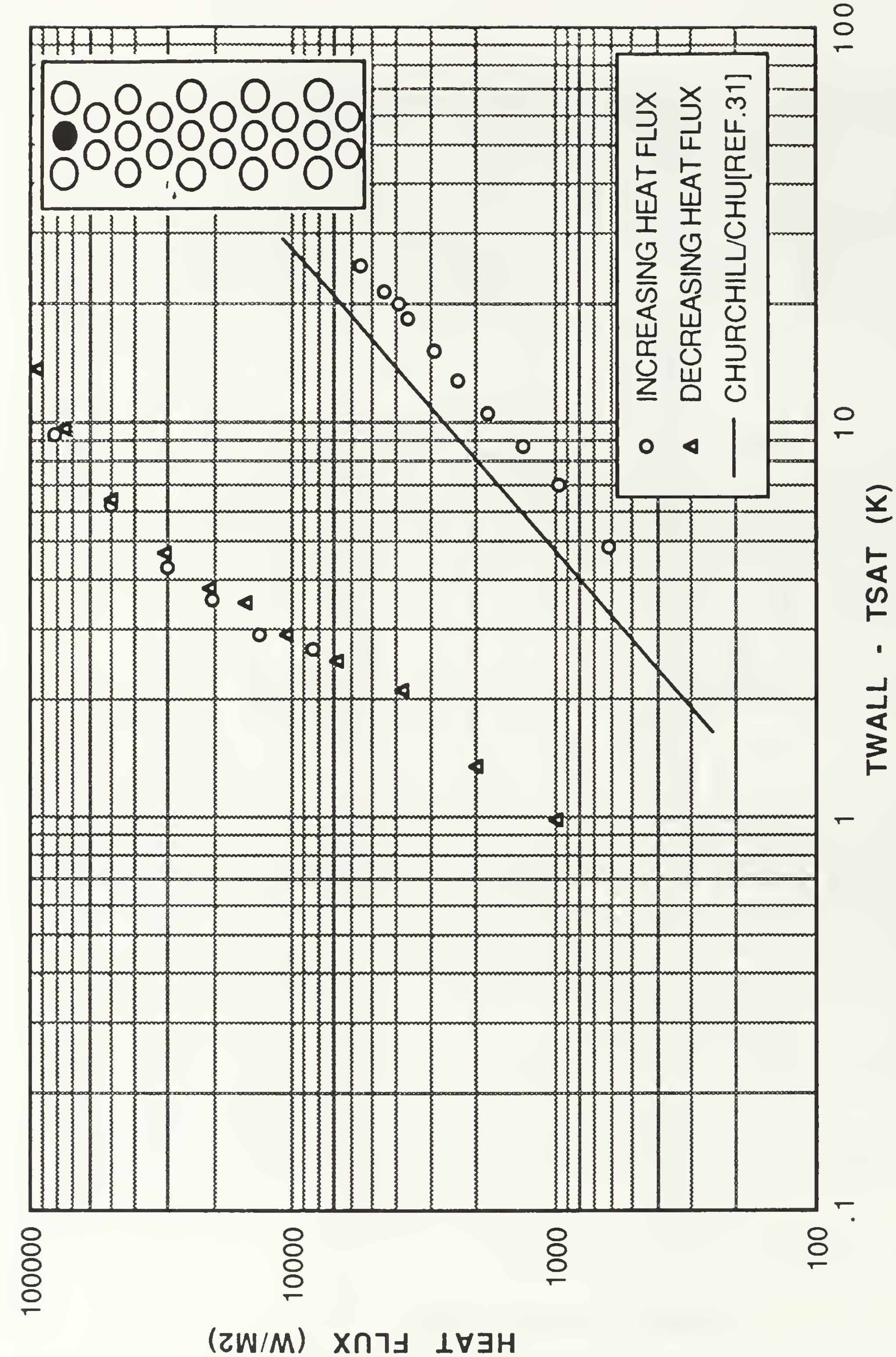

Figure 53. Performance of Tube 1 for Increasing/Decreasing Heat Flux in R-114 with 10% Oil

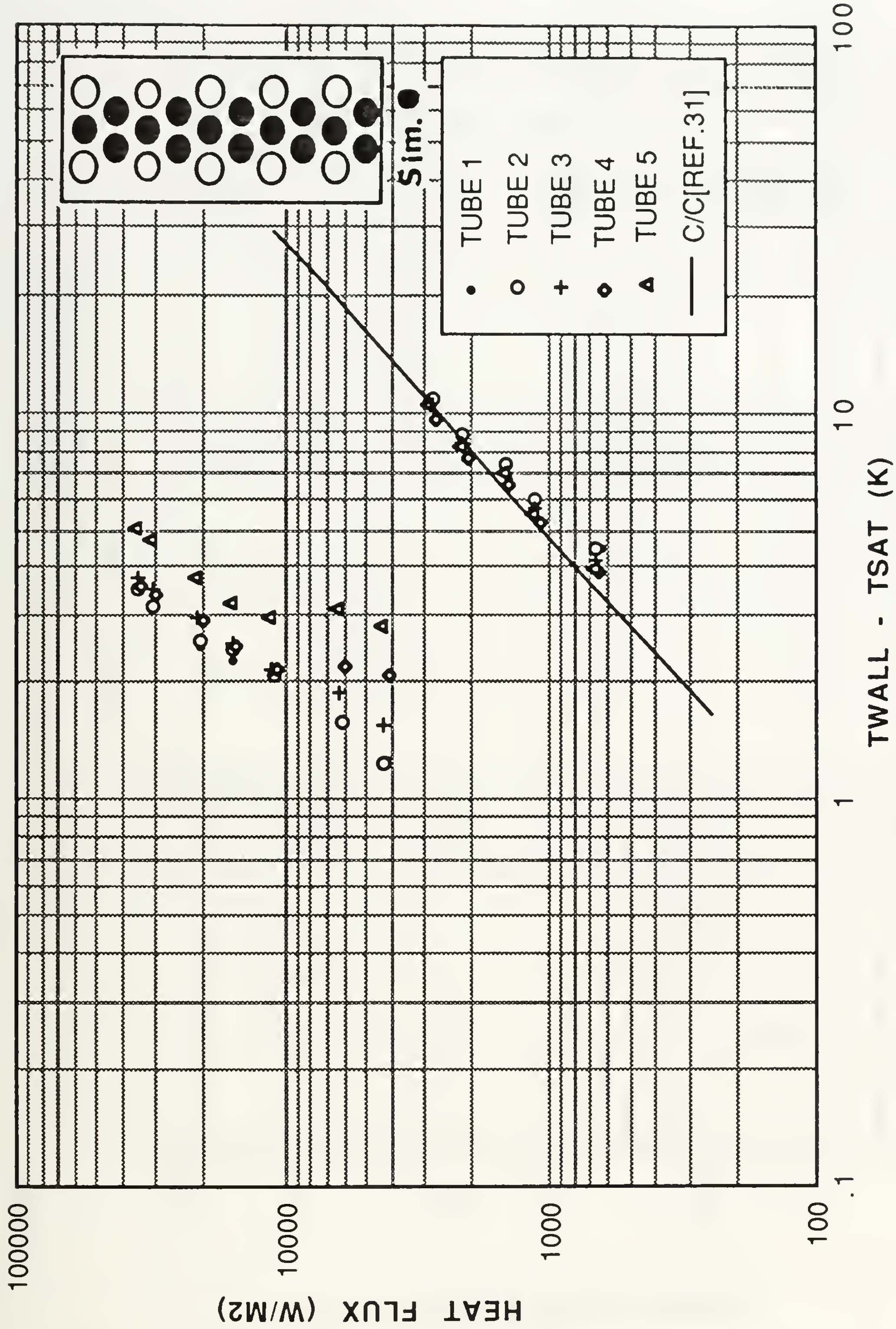

Figure 54. Performance of the Bundle with Simulation Heaters for Increasing Heat Flux in R-114 with 10% Oil

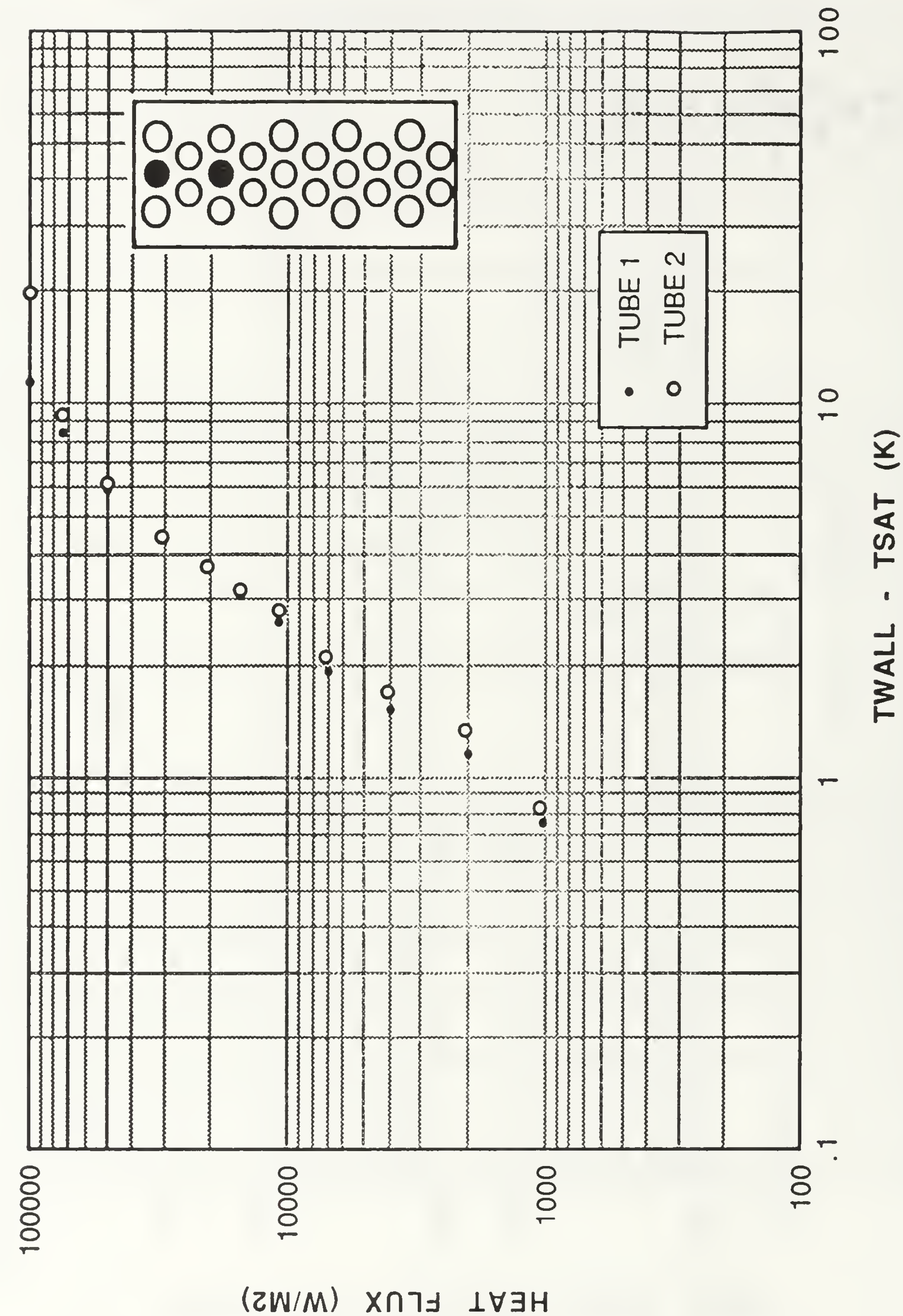

Figure 55. Performance of Tubes 1 and 2 for Decreasing Heat Flux in R-114 with 10% Oil

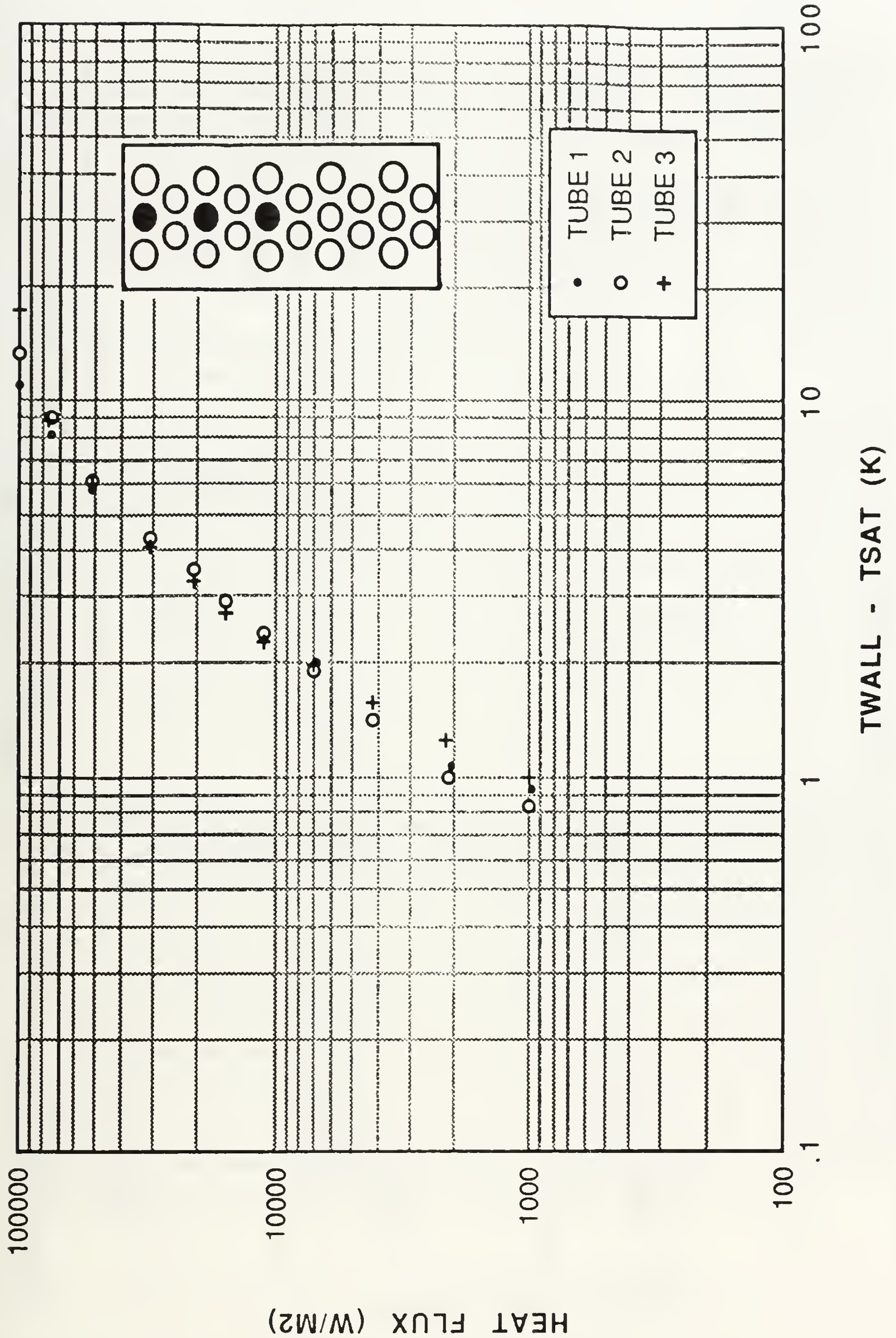

Figure 56. Performance of Tubes 1, 2, and 3 for Decreasing Heat Flux in R-114 with 10% Oil

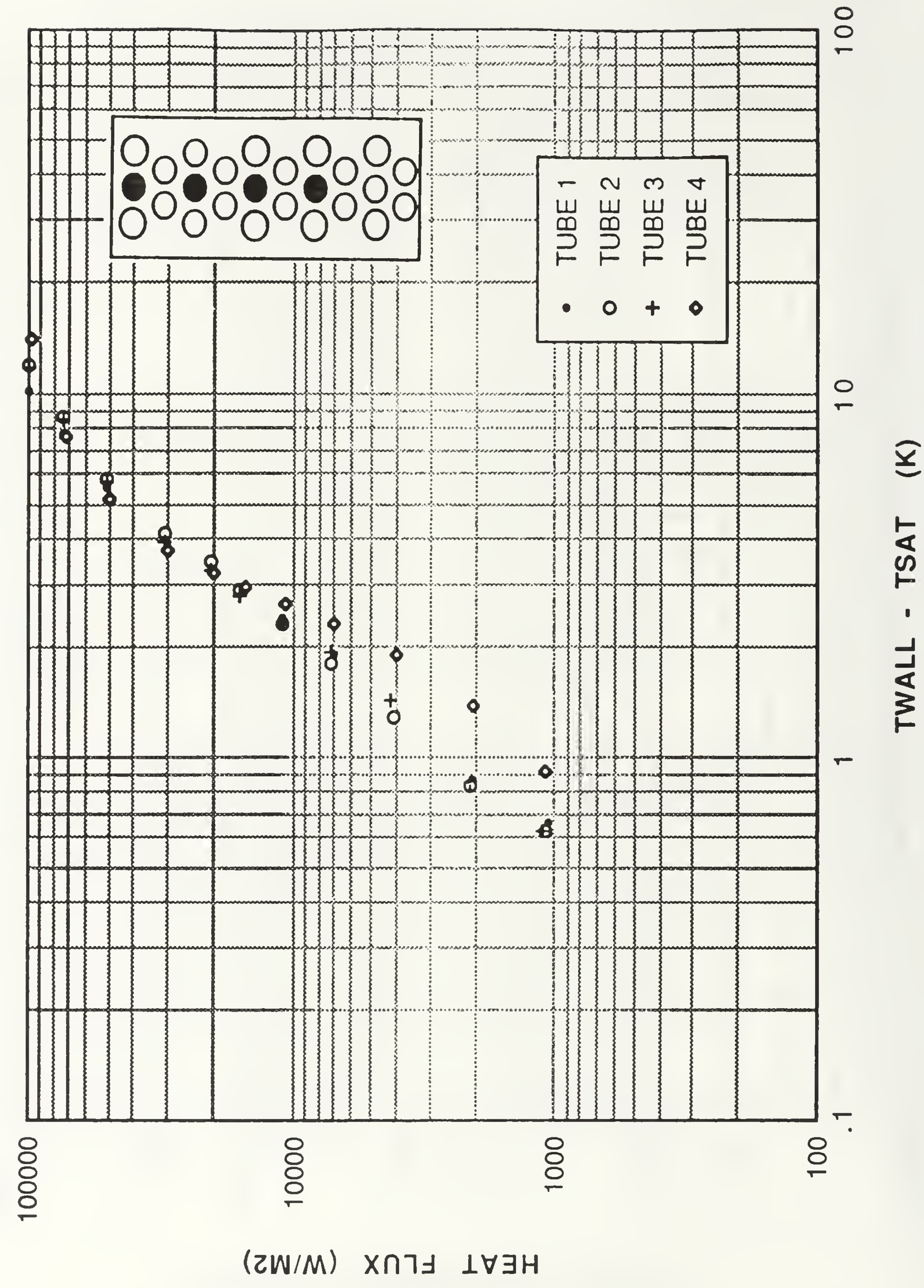

Figure 57. Performance of Tubes 1, 2, 3, and 4 for Decreasing Heat Flux in R-114 with 10% Oil

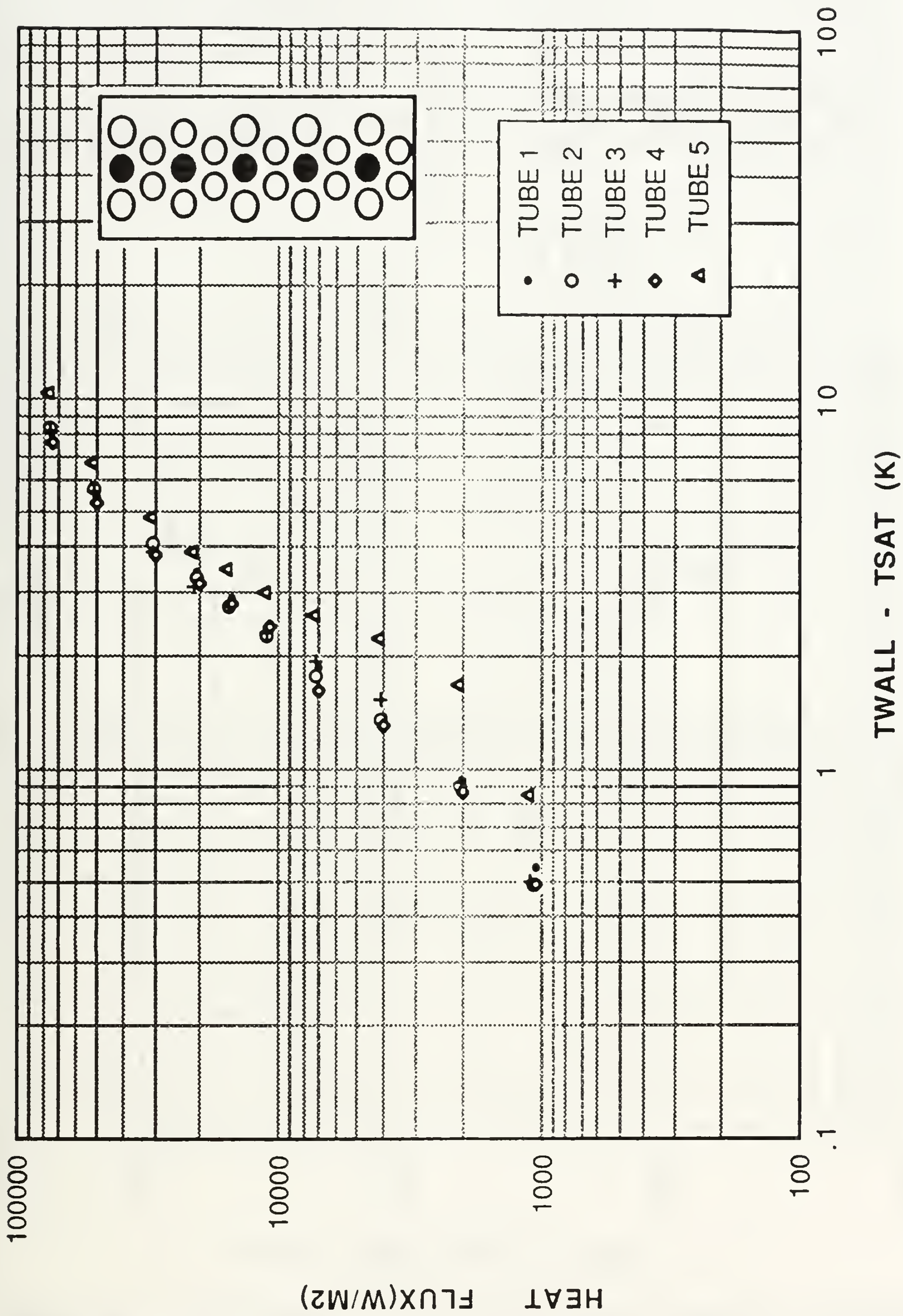

Figure 58. Performance of All Five Tubes for Decreasing Heat Flux in R-114 with 10% Oil

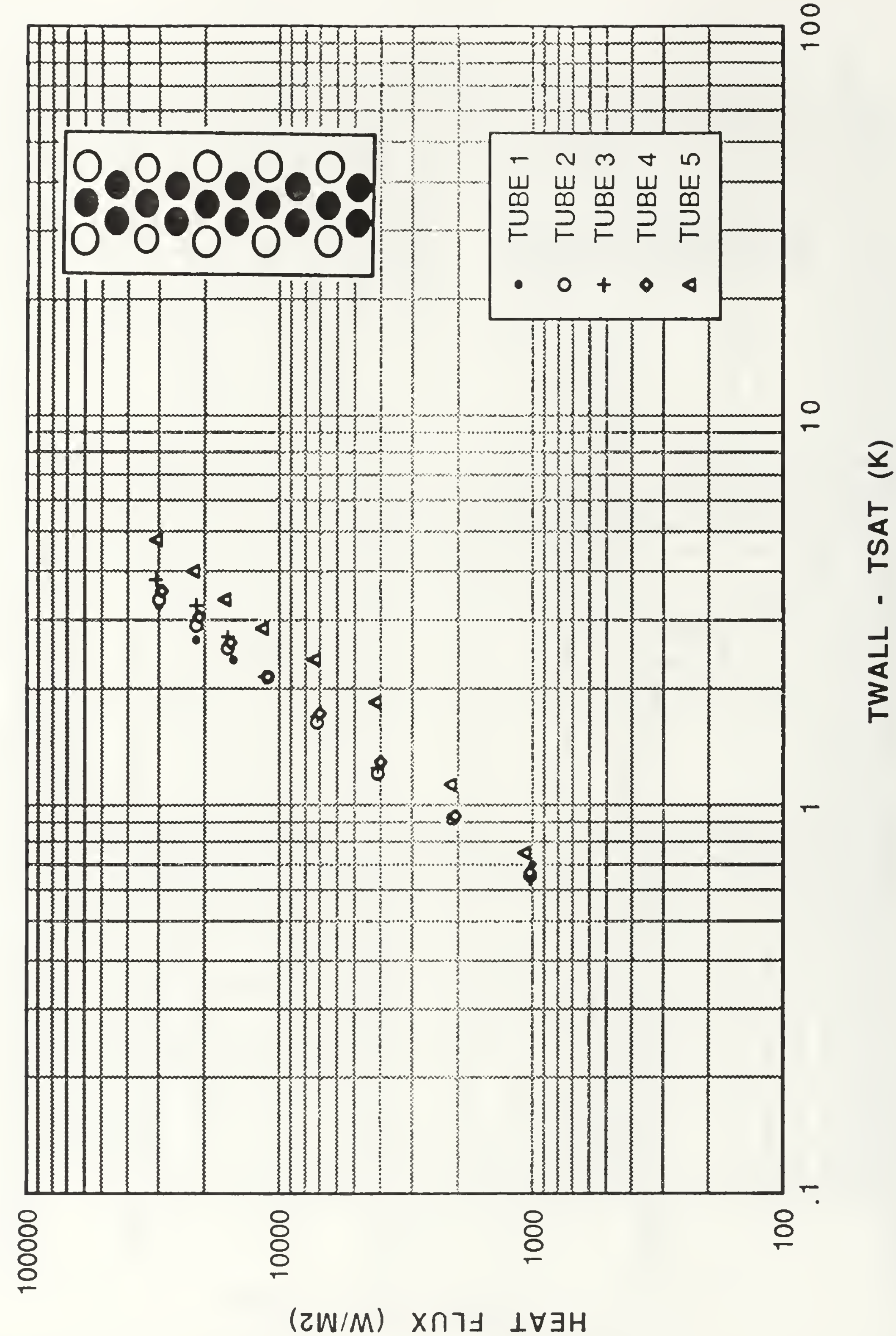

Figure 59. Performance of All Five Tubes with Active Pairs for Decreasing Heat Flux in R-114 with 10% Oil

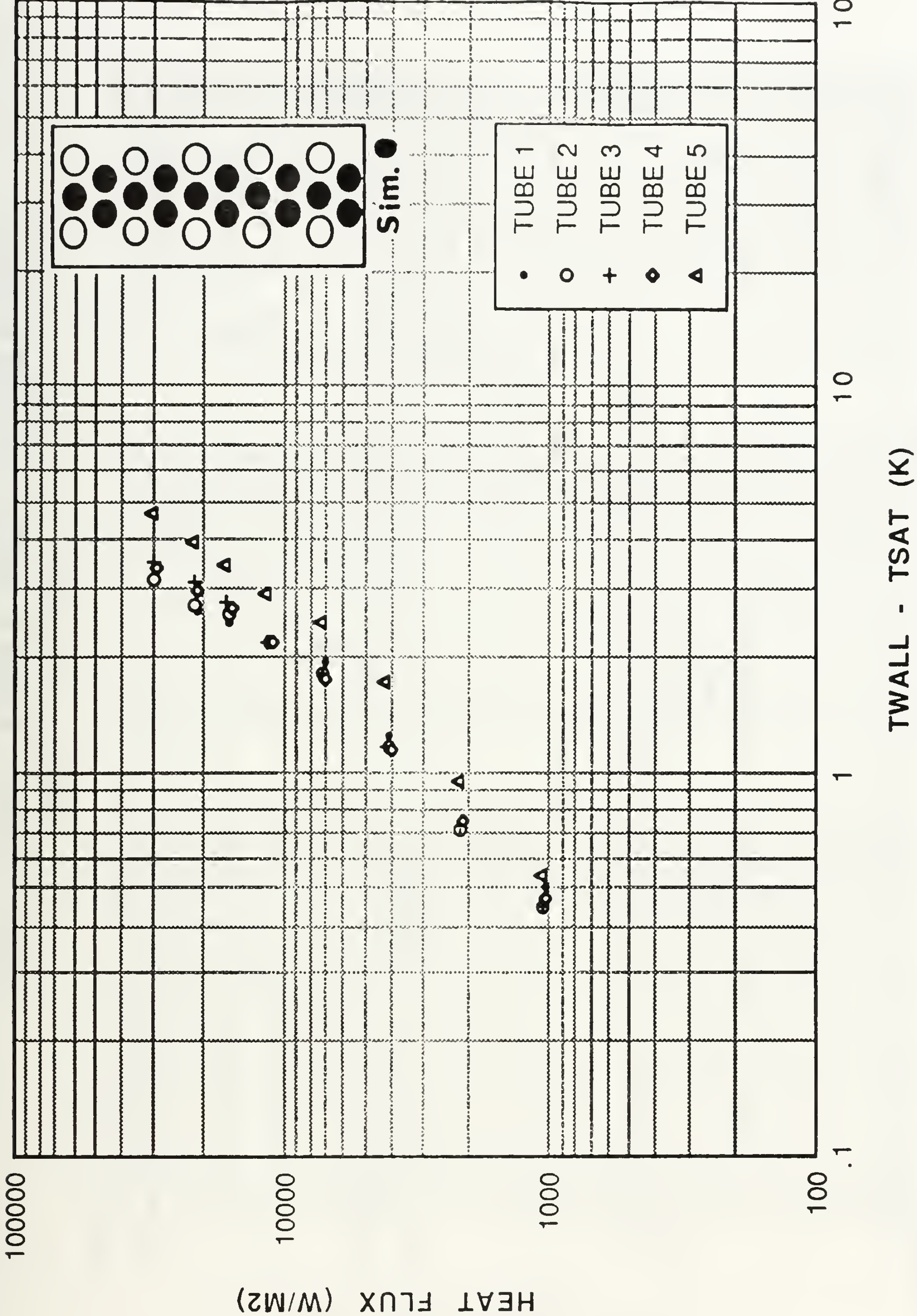

Figure 60. Performance of the Bundle with Simulation Heaters for Decreasing Heat Flux in R-114 with 10% Oil

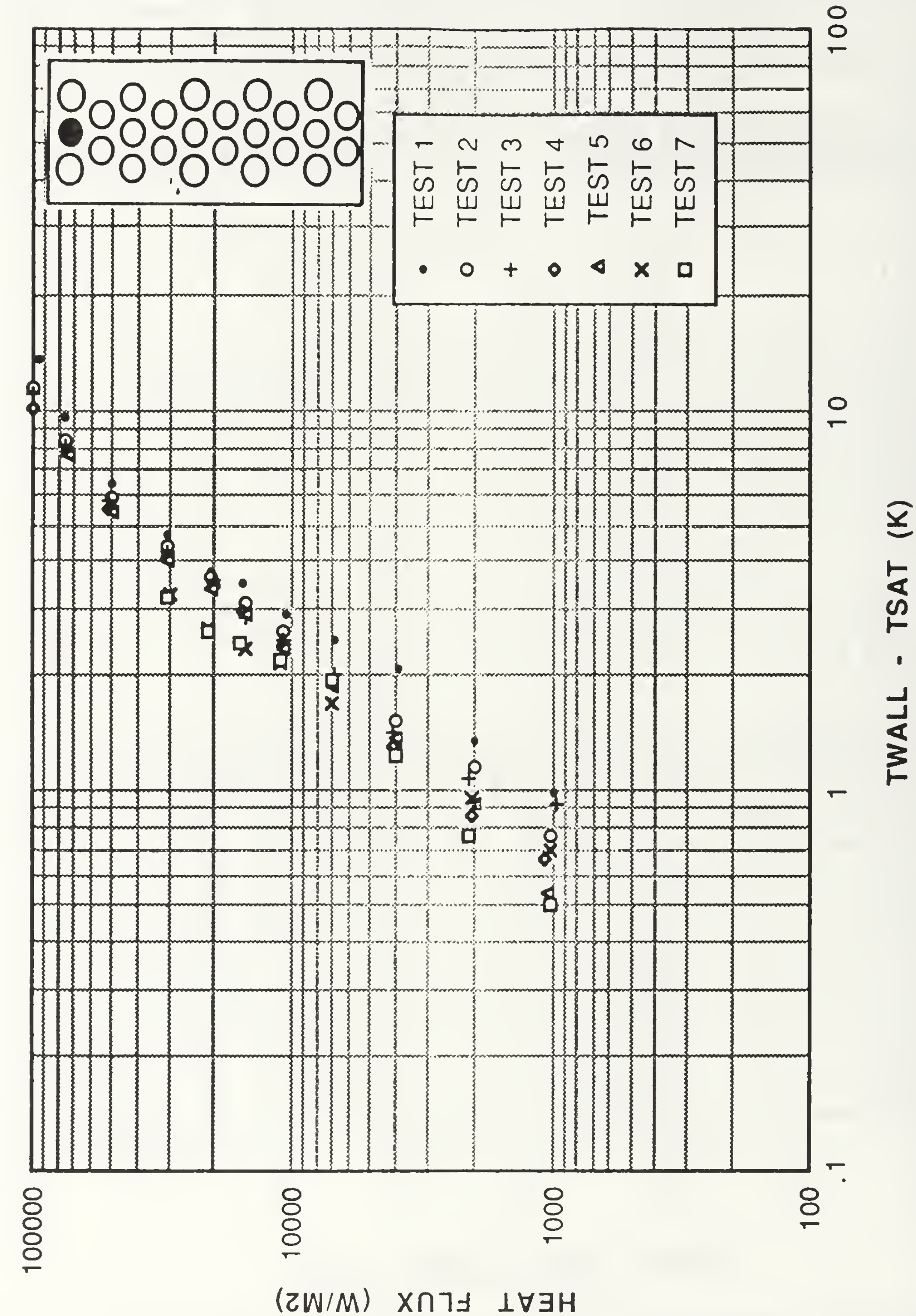

Figure 61. Comparison of Tests One to Seven for Tube 1 for Decreasing Heat Flux in R-114 with 10% Oil

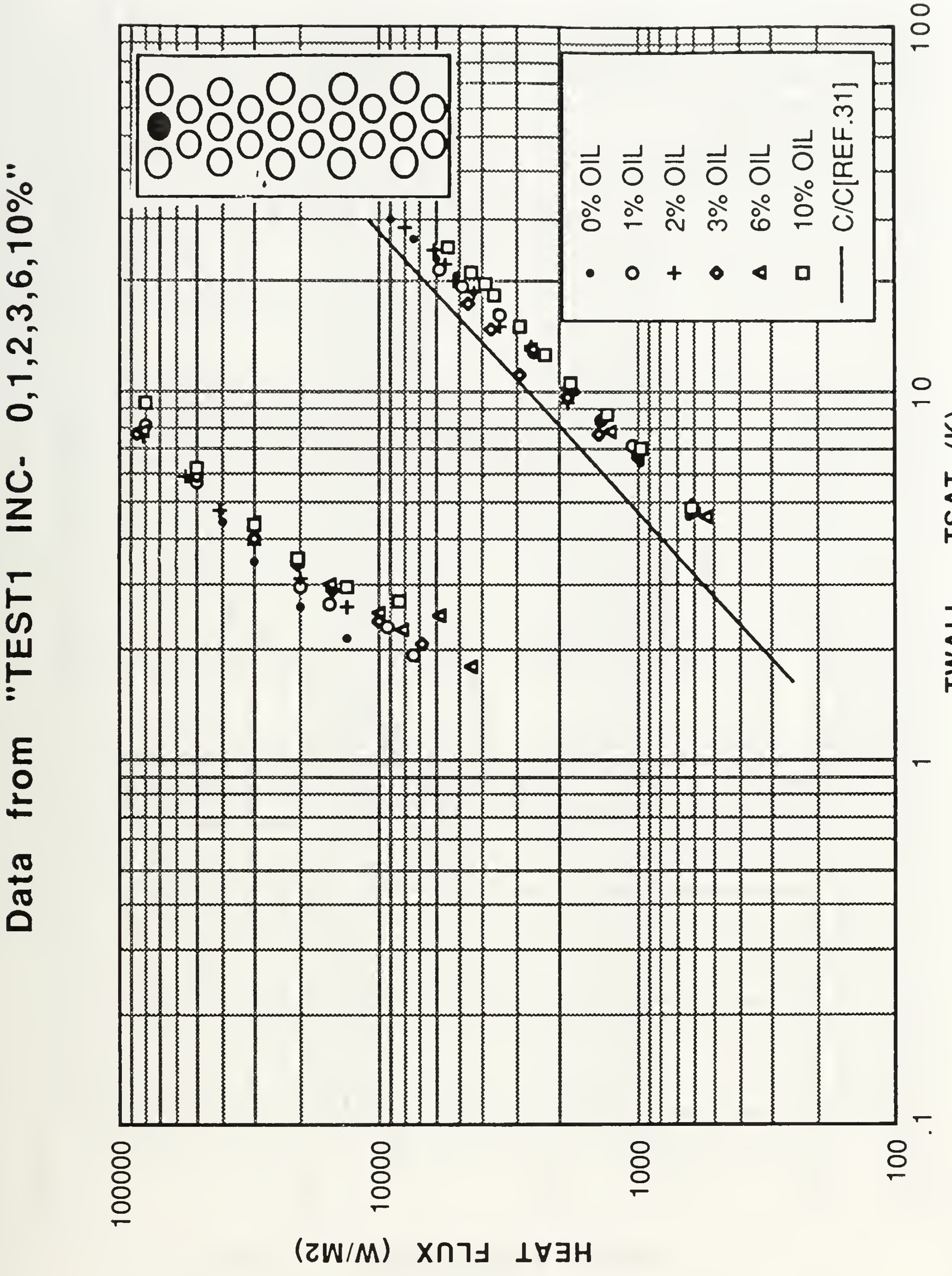

Figure 62. Comparison of Test One for Increasing Heat Flux in R-114 /Oil Mixtures

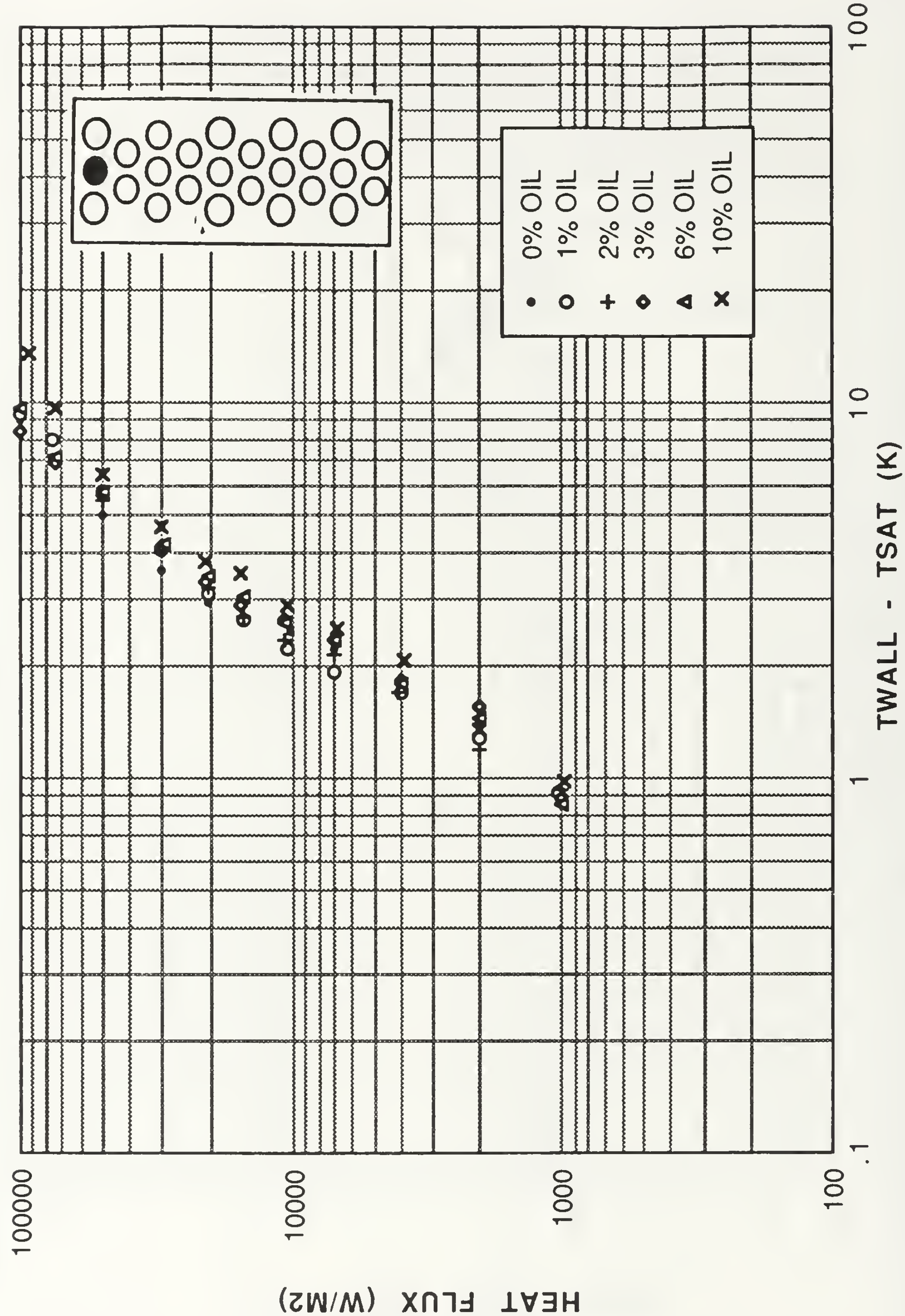

Figure 63. Comparison of Test One for Decreasing Heat Flux in R-114 /Oil Mixtures

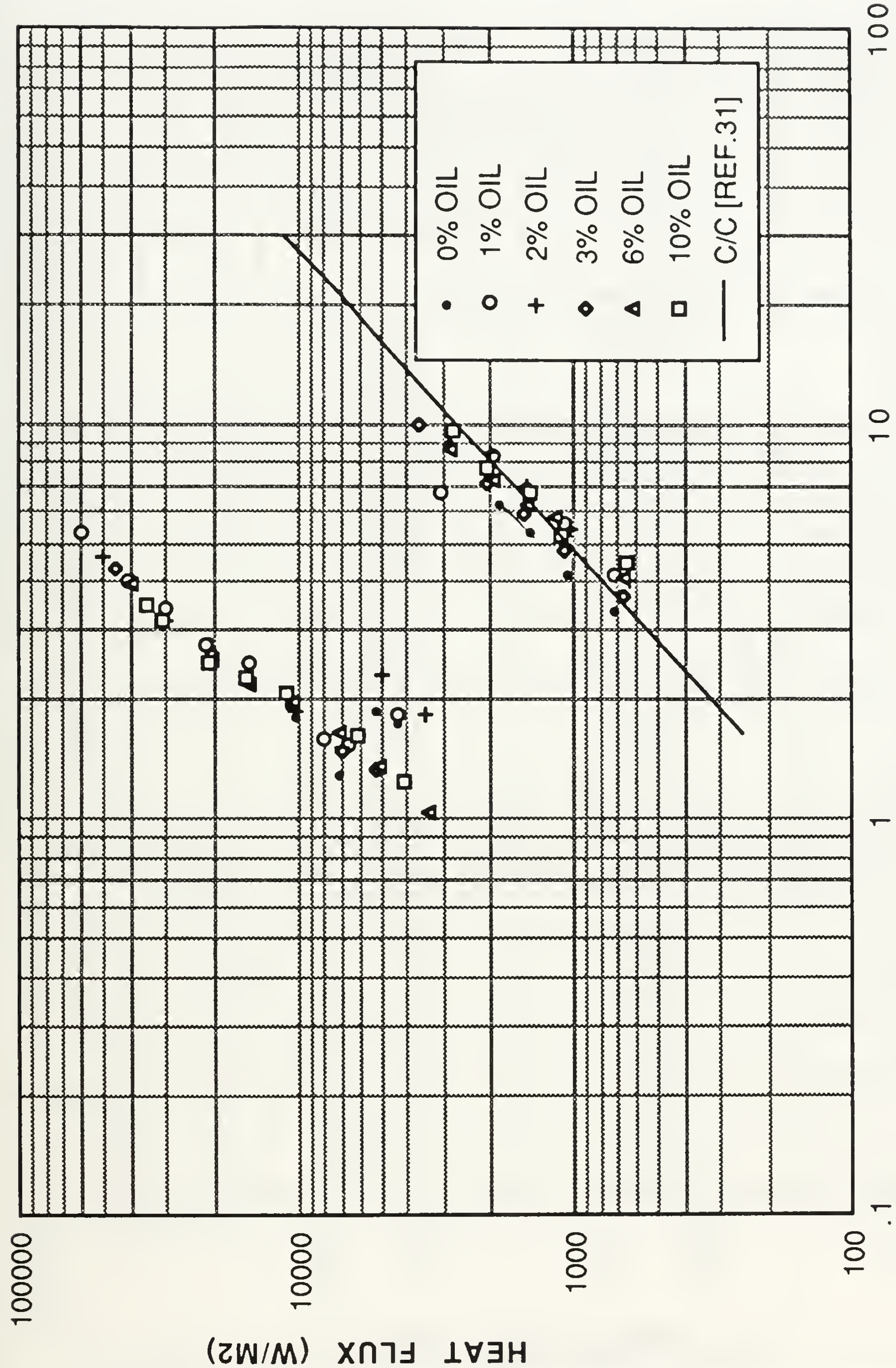

Figure 64. Comparison of Tests One to Seven Tube One for Increasing Heat Flux in R-114/Oil Mixtures

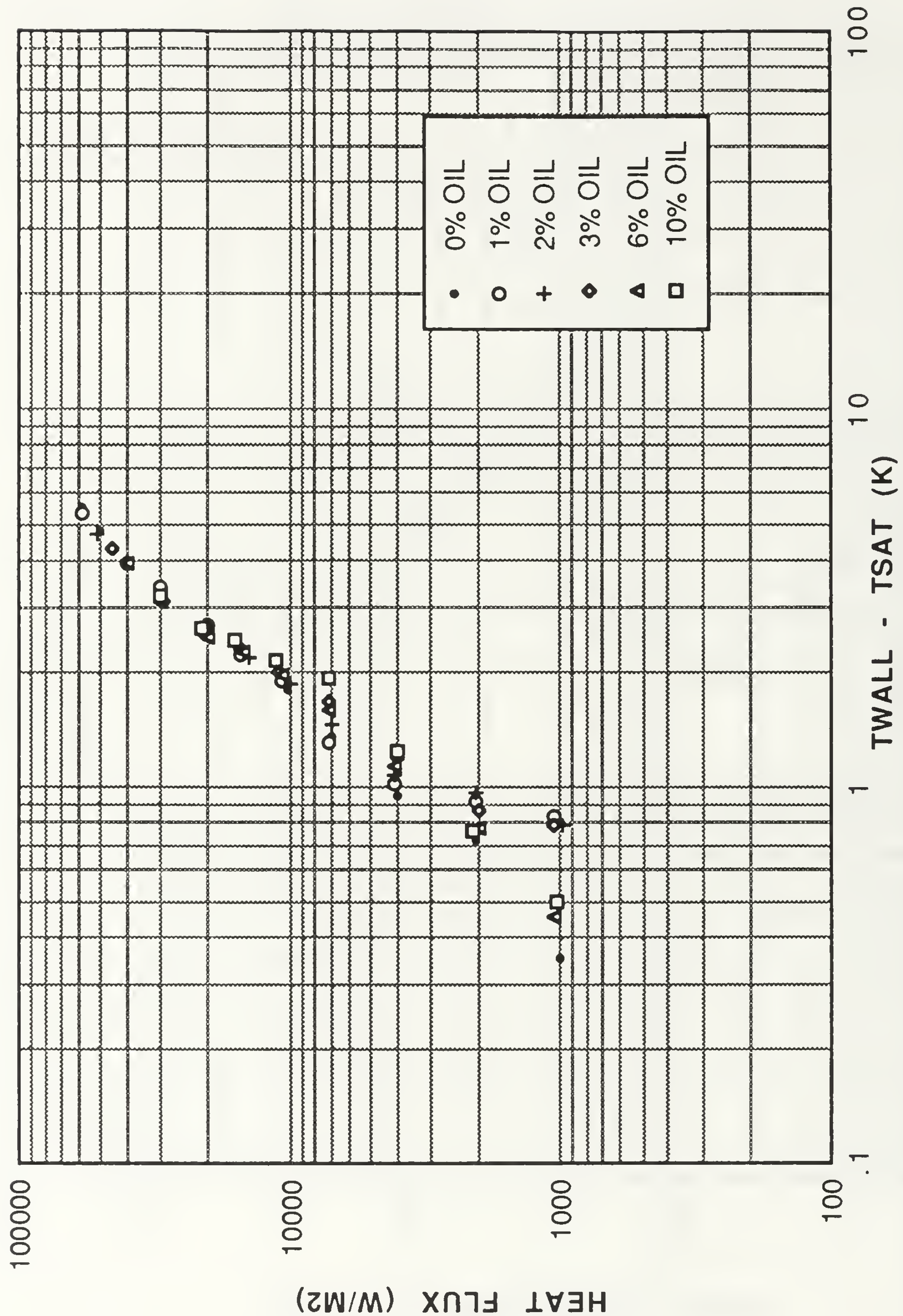

Figure 65. Comparison of Tests One to Seven Tube One for Decreasing Heat Flux in R-114/Oil Mixtures

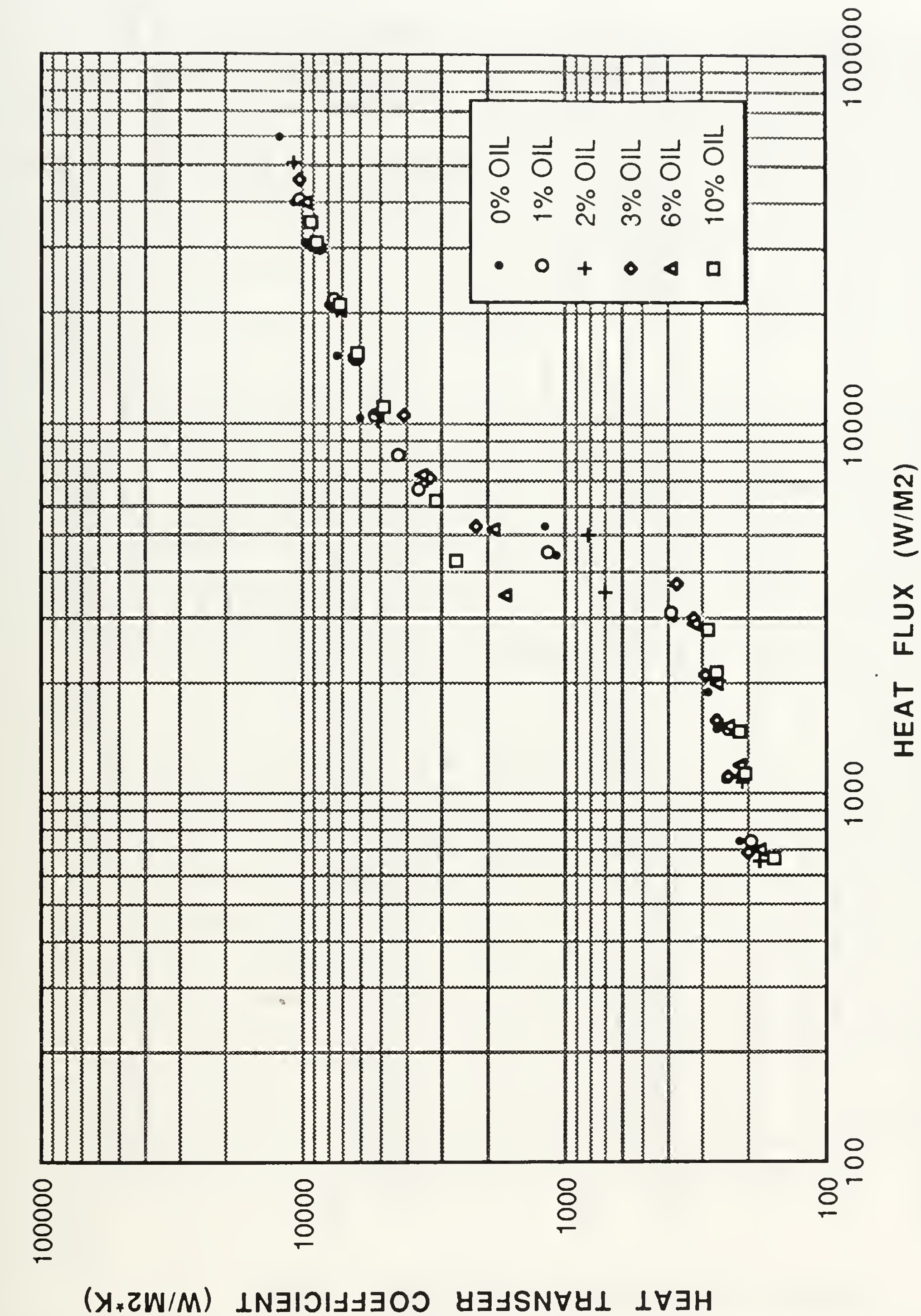

Figure 66. Mean Bundle Heat-Transfer Coefficient for Increasing Heat Flux in R-114/Oil Mixtures

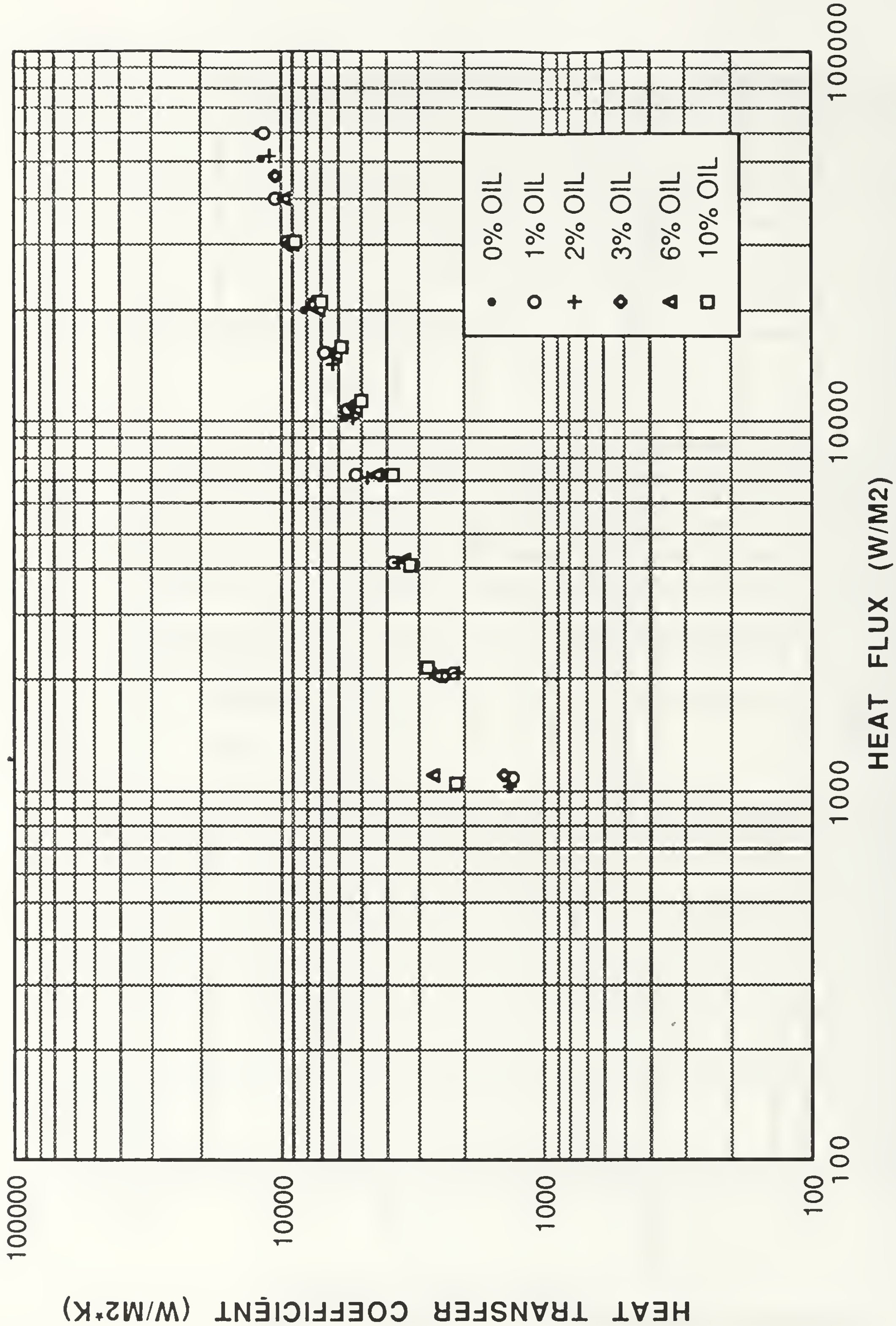

Figure 67. Mean Bundle Heat-Transfer Coefficient for Decreasing Heat Flux in R-114/Oil Mixtures

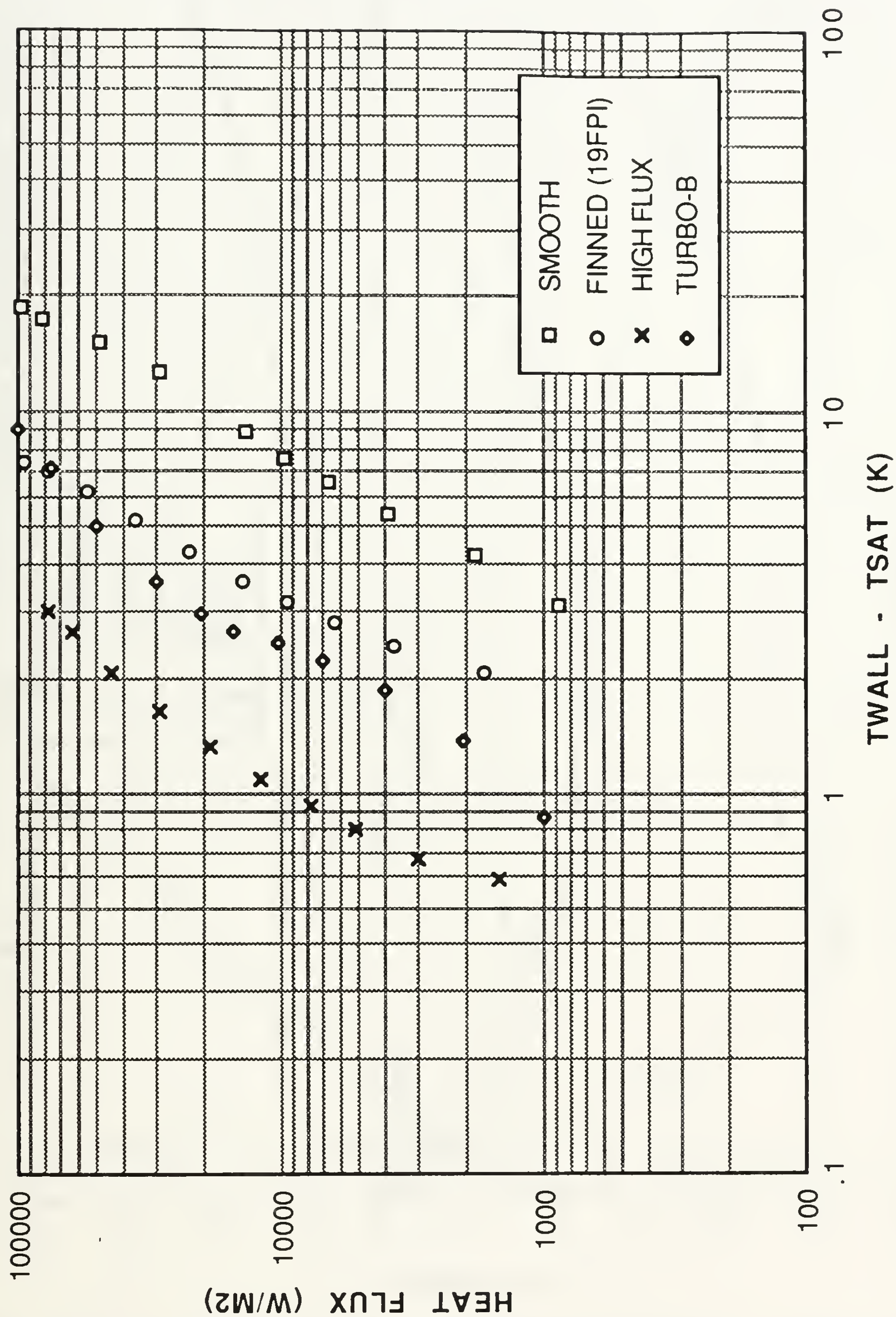

Figure 68. Test One Comparison of Turbo-B, Smooth, Finned, and High Flux Tube Bundles for Decreasing Heat Flux in Pure R-114

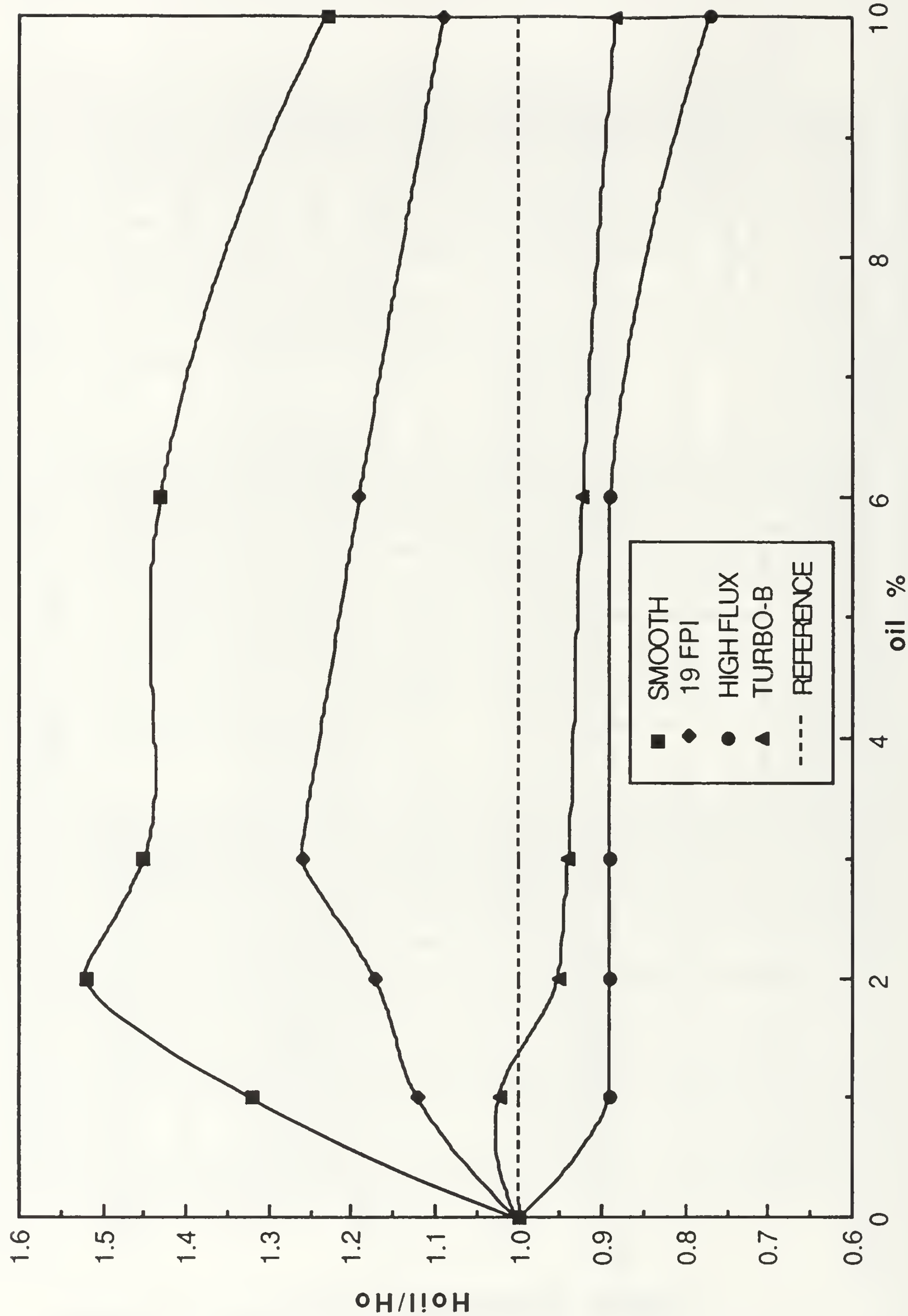

Figure 69. Ratio of Mean Bundle Heat-Transfer Coefficient With Oil to Heat-Transfer Coefficient Without Oil for Different Oil Percentages at a Heat Flux of 15 kW/m^2

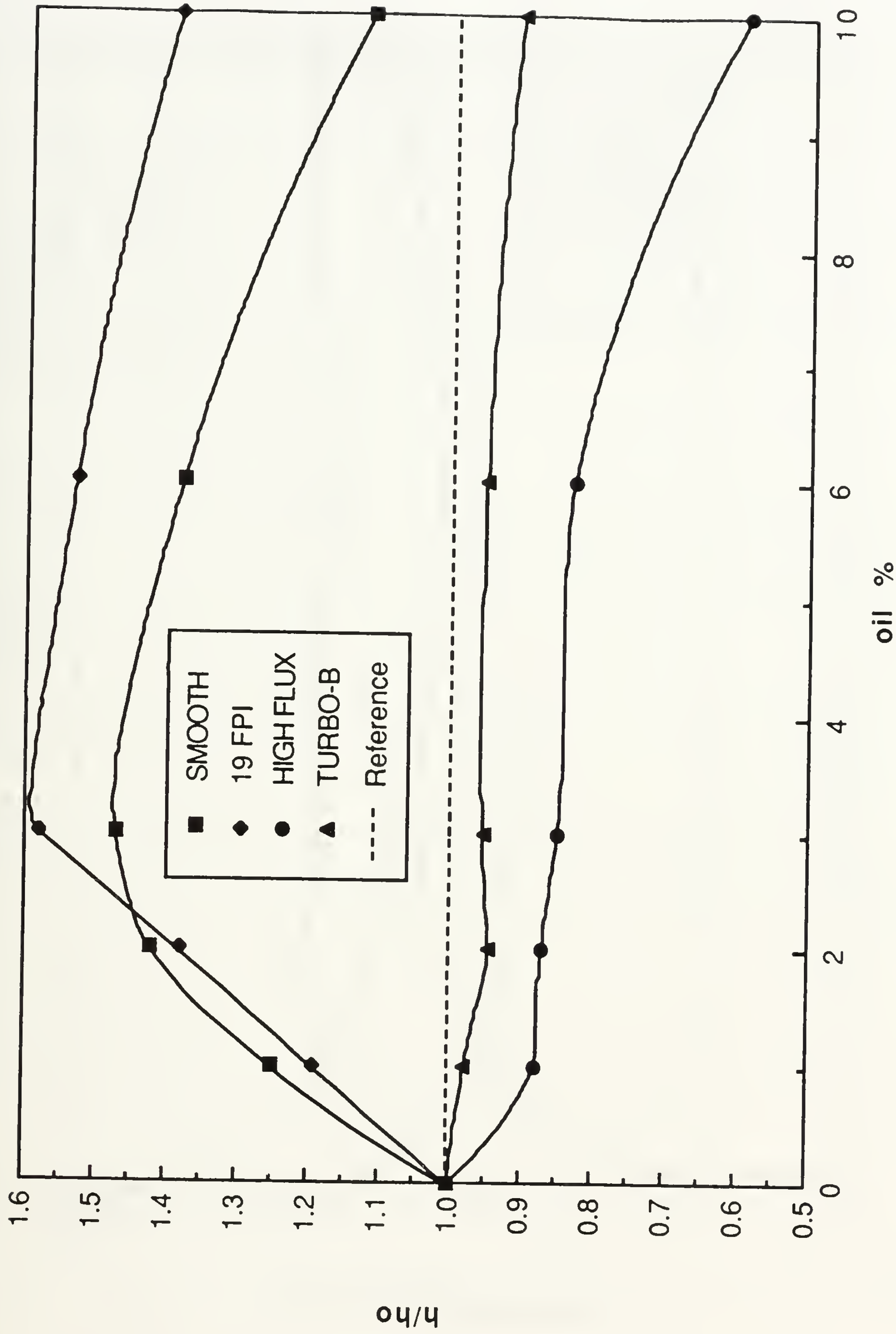

Figure 70. Ratio of Mean Bundle Heat-Transfer Coefficient With Oil to Heat-Transfer Coefficient Without Oil for Different Oil Percentages at a Heat Flux of 30 kW/m^2

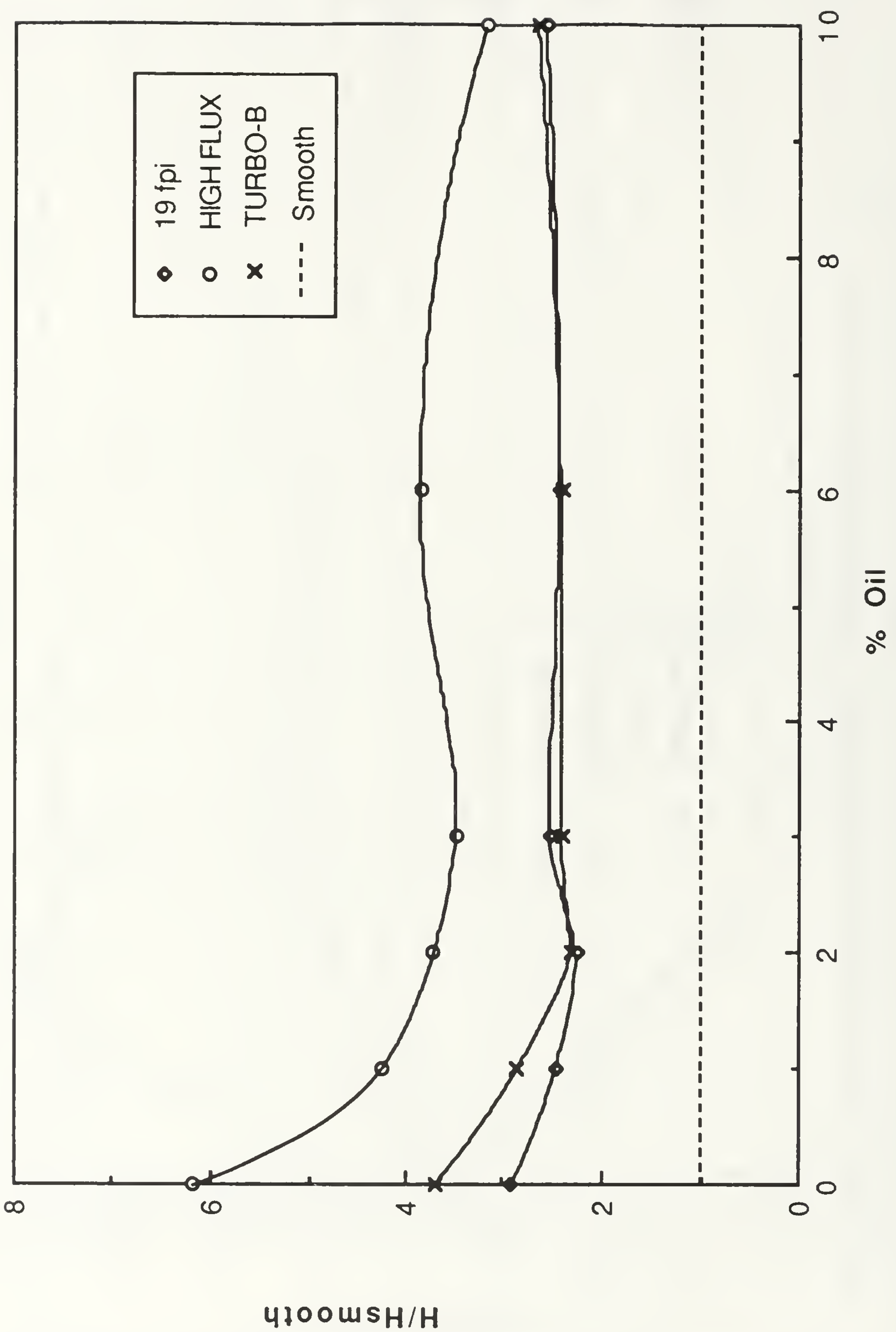

Figure 71. Ratio of Mean Bundle Heat-Transfer Coefficient of Enhanced Tube to Heat-Transfer Coefficient of Smooth Tube for Different Oil Percentages at a Heat Flux of 15 kW/m^2

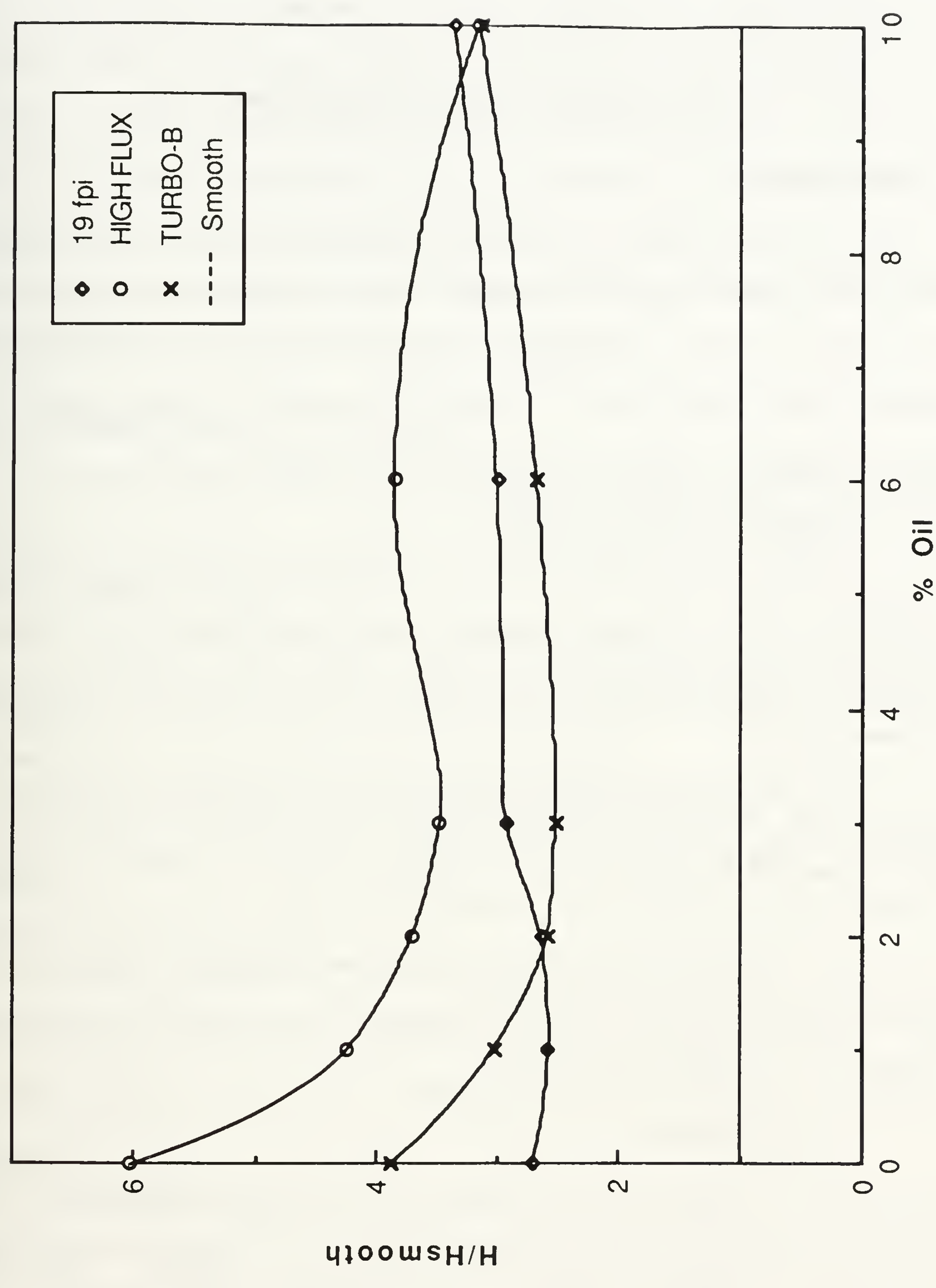

Figure 72. Ratio of Mean Bundle Heat-Transfer Coefficient of Enhanced Tube to Heat-Transfer Coefficient of Smooth Tube for Different Oil Percentages at a Heat Flux of 30 kW/m^2

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Nucleate boiling data of R-114 at atmospheric pressure were obtained using a small bundle of Turbo-B copper tubes. The data were obtained for both increasing and decreasing heat flux and at different oil concentrations. Based upon the results pertaining to this particular bundle and apparatus, the following conclusions may be made:

1. Natural Convection Region

a. For a single upper tube, a second lower tube directly below when turned on does increase the heat transfer performance of the upper tube, however when additional lower tubes are heated no net increase in performance occurs.

b. The presence of heated lower tubes in the bundle reduces the incipient boiling point of the upper tubes and the tubes tend to nucleate 'in order' (ie. top tube first, bottom tube last).

c. The effect of adding oil to the refrigerant (up to 10%) reduces the heat-transfer coefficient slightly (approximately 10-15%) due to changes in the fluid properties.

2. Boiling Region

a. For pure R-114, the presence of heated lower tubes on the top tube causes no enhancement at high heat fluxes (> 20 kW/m^2), but at low heat fluxes (< 20kW/m^2), there is a significant enhancement due to convective effects.

b. At very low heat fluxes (<2 kW/m^2), the presence of oil has little effect on the heat transfer performance of the top tube in the bundle. At higher heat fluxes (> 2kW/m^2), the performance is enhanced by 10-15% at low concentrations, but is degraded up to 20% at 10% oil concentration at the highest heat fluxes.

c. At typical operating heat fluxes (15-30 kW/m^2), the bundle performance is reduced between 5-15% with oil.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Conduct experiments with varying pool height, but keep the local pressure at each tube constant by simultaneously varying the vapor pressure above the pool.

2. Additional experiments with R-113 and R-114 should be conducted to investigate explosive (R-114) and partial (R-113) incipience at the onset of nucleation varying the time at the incipience.

3. Some instrumentation should be added such that the flowrates <u>through</u> the bundle can be determined. From these measurements, vapor quality can be determined.

4. Metal guide plates should be manufactured and placed on each side between the simulation tube bundle and the tube bundle itself. This further channels the flow of refrigerant thru the bundle at high heat fluxes.

5. Attention needs to be given to the question of refrigerant disposal. There are reclamation projects undertaken by most manufacturers; however, a method still needs to be found to remove the

refrigerant from the apparatus into a container suitable for such reclamation.

6. A high speed camera should be used to study the nucleation process and circulation patterns in more detail in the bundle. Neutrally buoyant particles might be placed in the pool to facilitate study of circulation patterns within the bundle.

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APPENDIX A: LIST OF DATA FILE

Table 3. DATA FILE NAMES FOR TURBO-B
TUBE BUNDLE EXPERIMENTS

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBI0001H	34	1 (15)	0	0	0
TBD0001H	38	1 (15)	0	0	0
TBI0001I	25	1 (13)	0	0	0
TBD0001I	22	1 (13)	0	0	0
TBI0001J	34	5	0	0	0
TBD0001J	25	1	0	0	0
TBI0002A	38	2	0	0	0
TBD0002	25	2	0	0	0
TBI0003A	38	3	0	0	0
TBD0003	27	3	0	0	0
TBI0004	34	4	0	0	0
TBD0004	24	4	0	0	0
TBI0005	34	5	0	0	0
TBD0005	24	5	0	0	0
TBI0006	32	5	0	5	0
TBD0006	26	5	0	5	0

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBI0007	31	5	0	5	5
TBD0007	24	5	0	5	5
TBI0101	33	1	1	0	0
TBD0101	23	1	1	0	0
TBI0107	29	5	1	5	5
TBD0107	26	5	1	5	5
TBI0201	38	1	2	0	0
TBD0201	22	1	2	0	0
TBI0207	25	5	2	5	5
TBD0207	20	5	2	5	5
TBI0301	34	1	3	0	0
TBD0301	25	1	3	0	0
TBD0302	24	2	3	0	0
TBD0303	22	3	3	0	0
TBD0304	24	4	3	0	0
TBD0305	24	5	3	0	0
TBD0306	21	5	3	5	0
TBI0307	26	5	3	5	5
TBD0307	21	5	3	5	5
TBI0601	32	1	6	0	0

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBD0601	22	1	6	0	0
TBD0602	22	2	6	0	0
TBD0603	24	3	6	0	0
TBD0604	22	4	6	0	0
TBD0605	24	5	6	0	0
TBD0606	21	5	6	5	0
TBI0607	27	5	6	5	5
TBD0607	21	5	6	5	5
TBI1001	33	1	10	0	0
TBD1001	22	1	10	0	0
TBD1002	27	2	10	0	0
TBD1003	24	3	10	0	0
TBD1004	24	4	10	0	0
TBD1005	23	5	10	0	0
TBD1006	16	5	10	5	0
TBI1007	24	5	10	5	5
TBD1007	17	5	10	5	5
TBI0001A	24	1	0	0	0
TBI0001C	27	1(15)	0	0	0
TBI0001D	33	1(13)	0	0	0

FILE NAME	NUMBER OF DATA POINTS	NUMBER OF INSTRUMENTED TUBE	PERCENT OF OIL	NUMBER OF ACTIVE PAIRS	NUMBER OF SIMULATION HEATERS
TBI0001E	33	1	0	0	0
TBI0001F	38	1	0	0	0
TBI0001G	38	1	0	0	0

APPENDIX B: SAMPLE CALCULATIONS

Data set number 1 Tube 1 of experiment TBD1005 (Turbo-B tube, decreasing heat flux, 10% oil concentration, test 5) was used for the sample calculations in order to validate the program used for data acquisition DRP4RH. The working fluid was R-114.

1. Test tube dimensions

   D_{tc} = 11.60 mm

   D_o = 14.15 mm

   D_i = 12.70 mm

   L = 203.2 mm

   L_u = 25.4 mm

2. Measured Parameters

   T1 = 10.62 °C

   T2 = 10.94 °C

   T3 = 9.96 °C

   T4 = 10.90 °C

   T5 = 10.04 °C

   T6 = 9.07 °C

   T1d1 = 2.27 °C

   T1d2 = 2.21 °C

   Aas = 3.513 V

Vas = 3.189 V

3. Calculations

The heaters power is first calculated for

q = Vas(V)xAas(V)x60(V/V)x1(A/V)

Note: The multiplication factors of volts and amp sensors are 60 and 1, respectfully.

Therefore:

q = (3.189)(3.513)(60V/V)(1A/V)

q = 672.19 Watts

The tube inside wall temperature is obtained from the average of all six thermocouple readings.

$$\overline{T}_{wi} = \frac{1}{6}\sum_{n=1}^{6} T_n$$

= 1/6(10.62 + 10.94 + 9.96 + 10.90 + 10.04 + 9.07)

= 10.25 °C

The tube outside temperature is calculated by knowing the inside wall temperature using Fourier's Conduction Law. Uniform radial conduction is assumed.

$$\overline{T}_{wo} = \overline{T}_{wi} - \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

where the second term on the right hand side is the Fourier conduction term. If we define this term as

$$\phi = \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

and

$$\theta_b = \overline{T}_{wo} - Tsat_c$$

where k_{cu} is the thermal conductivity of copper and is calculated as follows

$$k_{cu} = 434.0 - [0.112(\overline{T}_{wi})]$$

$$k_{cu} = 434.0 - [0.112(283.25)]$$

$$k_{cu} = 402.28\ W/mK$$

now

$$\overline{T}_{wo} = \overline{T}_{wi} - \frac{672.19[\ln(\frac{14.15}{11.60})]}{2\pi(402.28)(.2032)}$$

$$\overline{T}_{wo} = (10.25 - .2601)^{\circ}C$$

$$\overline{T}_{wo} = 9.98^{\circ}C$$

The liquid saturation temperature at the top of the tube bundle is

$$Tsat = \frac{tld1 + Tld2}{2}$$

$$Tsat = \frac{2.27 + 2.21}{2}$$

$$Tsat = 2.24\,^{\circ}C$$

In order to calculate the local saturation temperature for each tube, correction factors are needed to account for hydrostatic pressure differences between the tube locations and the liquid free surface. This difference is calculated by:

$$\Delta P = \rho(g)(ht)$$

For the top tube in the bundle which is 0.124 m below the thermocouple measuring pool temperature.

$$\Delta P = 1523.12(9.81)(0.124)$$

$$\Delta P = 1852.78\ Pa$$

For 1852.78 Pa pressure difference, corrected saturation temperature is obtained by adding 0.04 °C (from standard tables for R-114) to Tsat. Corrected Tsat is:

$$Tsat_c = (2.24 + 0.04)\,^{\circ}C$$

$$Tsat_c = 2.28\,^{\circ}C$$

Therefore, the wall superheat can be obtained by the following:

$$\theta_b = \overline{Two} - Tsat_c$$

$$\theta_b = (9.98 - 2.28)\,^{\circ}C$$

$$\theta_b = 7.70^{\circ}\,C$$

Now that the wall superheat is known, we need to calculate the heat flux and the heat-transfer coefficient. To do this, we know that the tube is 12 inches long and is heated in a eight inch center portion of the tube. The unheated lengths of the tube are a one inch and a three inch section on opposite ends of the tube. These unheated lengths have a fin effect during the heat transfer process to the evaporating refrigerant. In order to account for this, the following procedure was adopted for both one and three inch sections. Calculations are shown below for the one inch section. Heat transfer from the unheated end is calculated as heat from the base of the fin:

$$q_f = [(h_b)(p)(k_{cu})(A_c)]^{0.5}(\theta_b)(\tanh[(n)(L_c)])$$

where

$$p = \pi\,(D_o)$$

$$= \pi\,(.01415)\text{ m}$$

$$= .04445\text{ m}$$

now

$$A_c = \pi/4(D^2_o - D^2_i)$$

$$= \pi/4(.01415^2 - .01270^2)$$

$$= 3.0578 \times 10^{-5}\text{ m}^2$$

The corrected length of unenhanced surface at the end was calculated as follows

$$L_c = L_u + (t/2)$$

$$= 0.0254 + [(0.01415-0.0127)/2]$$

$$= 0.0258 \text{ m}$$

h_b is the natural convection heat transfer coefficient of the fin like ends and was calculated by using Churchill-Chu [Ref. 22] correlation for natural convection for a smooth cylinder, as modified by Pulido [Ref.27].

$$h_b = \frac{k}{D_o}[0.6+.387\frac{[\frac{[g(\beta)(D_o^3)(\theta_b)(\tanh(nL_c))]}{\nu(\alpha)(L_c)(n)}]^{1/6}}{[1+[\frac{.559}{Pr}]^{9/16}]^{8/27}}]^2$$

where

$$n = [\frac{(h_b)(p)}{(k_{cu})(A_c)}]^{0.5}$$

Therefore an iterative technique was necessary to calculate h_b. The iterative technique used was to assume h_b was 190 W/m^2K and continue the iteration until successive values are within 0.001 of each other. The fluid physical properties are calculated at the vapor mean film temperature, given by the following equation.

$$T_{film} = \frac{Tsat_c + \overline{Two}}{2}$$

$$T_{film} = \frac{2.28 + 9.98}{2}$$

$$T_{film} = 6.13^{\circ}\,C = 279.13^{\circ}\,K$$

For R-114, the physical properties are given in the program by:

Dynamic viscosity, T_{film} in ^{o}K

$$\mu = \exp[-4.4636 + (1011.47/T_{film})]\times 10^{-3}$$

$$\mu = 430.927\times 10^{-6} \text{ kg/m s}$$

Specific heat, T_{film} in ^{o}K

$$C_p = [0.40188 + 1.65007\times 10^{-3}(T_{film}) + 1.51494\times 10^{-6}(T_{film}{}^{2}) - 6.67853\times 10^{-10}(T_{film}{}^{3})]\times 10^{3}$$

$$C_p = 966.31 \text{ J/kgK}$$

Density, T_{film} in ^{o}K

$$\rho = 16.0184533\,(36.32 + 61.146414\psi^{1/3} + 17.476838\psi^{1/2} + 1.119828\psi^{2})$$

where

$$\psi = 1 - \frac{[1.8(Tfilm)]}{753.95}$$

and

$$\psi = .333$$

$$\rho = 1512.09\ \frac{kg}{m^{3}}$$

Thermal conductivity of R-114, T_{film} in ^{o}C

$$k = 0.071 - (0.000261)(T_{film})$$

$k = 6.936 x 10^{-2}$ W/mK

Prandtl Number

$Pr = [(Cp)\mu]/k$

$Pr = 6.003$

Thermal Expansion Coefficient

$\beta = -(1/\rho)(\Delta\rho/\Delta T)$

$\rho_{279.03} = 1512.395 \frac{kg}{m^3}$

$\rho_{279.23} = 1511.824 \frac{kg}{m^3}$

$\beta = -(1/1512.395)[(.571)/(0.2)]$

$\beta = 1.89 x 10^{-3}\ (1/K)$

Kinematic viscosity

$\nu = \frac{\mu}{\rho}$

$\nu = \frac{430.927 x 10^{-6}}{1512.09}$

$\nu = 2.849 x 10^{-7}\ m^2/s$

Thermal Diffusivity

$$\alpha - \frac{k}{(\rho)C_p}$$

$$\alpha - \frac{6.936x10^{-2}}{(1512.09)966.31}$$

$$\alpha - 4.747x10^{-8}\ m^2/s$$

Knowing the above properties, the heat-transfer coefficient h_b, can be obtained by iteration

$h_b =$ 362.57 W/m^{2}K

Knowing this we can calculate n

$$n - [\frac{(h_b)(p)}{(k_{cu})(A_c)}]^{0.5}$$

$$n - [\frac{(362.57)(44.45x10^{-3})}{(402.28)(3.0578x10^{-6})}]^{0.5}$$

$$n - 36.19$$

then we can obtain q_f

$$q_f - [(h_b)(p)(k_{cu})(A_c)]^{0.5}(\theta_b)(\tanh[(n)(L_c)])$$

$$q_f - [(362.57)(.04445)(402.28)(3.0578x10^{-5})]^{0.5}$$
$$(7.70)(\tanh[(36.196)(0.0258)])$$

$$q_f - 2.51\ W$$

The corresponding results for the three inch section are

$h_b = 289.47 \ W/m^2K$

$q_f = 1.24 \ W$

Therefore, the heat transfer through the heated length of the tube is

$q_s = q - qf$ (1 inch section) $- qf$ (3 inch section)

$q_s = (672.19 - 1.24 - 2.51) \ W$

$q_s = 668.35 \ W$

and the heat flux and the heat transfer coefficient are as follows

$q'' = q_s/A_s$

$= q_s/((\pi)(D_o)(L))$

$= (668.35)/((\pi)(0.01415)(.2032))$

$= 7.398 \times 10^4 \ W/m^2$

and finally the heat transfer coefficient

$$h = \frac{q_s}{A_s(T_{wo} - Tsat)}$$

$$h = \frac{668.35}{9.033 \times 10^{-3}(7.70)}$$

$$h = 9.609 \times 10^3 \ W/m^2K$$

APPENDIX C: UNCERTAINTY ANALYSIS

The same data run (TBD1005) was chosen for the uncertainty analysis. Therefore, the measured and calculated parameters found in the sample calculation were used in this section. The unceratainty analysis performed was for a high heat flux, but the procedure could be performed at any heat flux to determine the uncertainty bands. All uncertainties are presented as a percentage of the calculated parameter. The uncertainty associated with the experimental parameters is calculated from the equation suggested by Kline and McClintock [Ref. 35]. For example:

$R = R(x_1, x_2, \ldots\ldots, x_n)$

then

$$\delta R = [(\frac{\partial R}{\partial x_1}\delta x_1)^2 + (\frac{\partial R}{\partial x_2}\delta x_2)^2 + \ldots\ldots + (\frac{\partial R}{\partial x_n}\delta x_n)^2]^{0.5}$$

where

δR = uncertainty of the desired dependant variable

x_n = measured variables

δx_n = uncertainty in measured variables

The boiling heat-transfer coefficient is given by

$$h = \frac{q_s}{A_s(\overline{T}_{wo} - Tsat)}$$

where

$$\overline{T}_{wo} = \overline{T}_{wi} - \frac{q[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

In the above equation, the second term on the right hand side is usually called the Fourier heat-transfer conduction term. If we define this as

$$\phi = \frac{q\left[\ln\left(\frac{D_o}{D_{tc}}\right)\right]}{2\pi\,(k_{cu})\,(L)}$$

and

$$\theta_b = \overline{T}_{wo} - Tsat_c$$

With this notation, the uncertainty in the heat-transfer coefficient is obtained using the following equation.

$$\frac{\delta h}{h} = \left[\left(\frac{\delta q}{q}\right)^2 + \left(\frac{\delta A_s}{A_s}\right)^2 + \left(\frac{\delta \overline{T}_{wi}}{\theta_b}\right)^2 + \left(\frac{\delta \phi}{\theta_b}\right)^2 + \left(\frac{\delta Tsat}{\theta_b}\right)^2\right]^{0.5}$$

where

q= VxI

q= V(V)xI(V)x60(V)x1(A/V)

and the uncertainty is

$$\frac{\delta q}{q} = \left[\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta I}{I}\right)^2\right]^{0.5}$$

The accuracy in the voltage and current sensors are as follows

$\delta Vas = \pm 0.05\ V$ $\delta Aas = \pm 0.025\ A$

From the sample calculation section

Vas = 3.189 V Aas = 3.513 V

Therefore,

$$\frac{\delta q}{q} = [(\frac{\delta Vas}{Vas})^2 + (\frac{\delta Aas}{Aas})^2]^{0.5}$$

$$\frac{\delta q}{q} = [(\frac{0.05}{3.189})^2 + (\frac{0.025}{3.513})^2]^{0.5}$$

$$\frac{\delta q}{q} = 1.72\ percent$$

Calculation of the uncertainty of the surface area is as follows

$A_s = \pi(D_o)(L)$

$$\frac{\delta A_s}{A_s} = [(\frac{\delta D_o}{D_o})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

Knowing the dimensions of the tube from the manufacturer and estimated inaccuraccies from work shop tools and human error, the unceratinty was calculated.

Dimensions

D_o = 14.15 mm L = 203.2 mm

Inaccuracies in measurements

δD_o= 0.1 mm δL = 0.2 mm

Uncertainty analysis performed

$$\frac{\delta A_s}{A_s} = [(\frac{\delta D_o}{D_c})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

$$\frac{\delta A_s}{A_s} = [(\frac{0.1}{14.15})^2 + (\frac{0.2}{203.2})^2]^{0.5}$$

$$\frac{\delta A_s}{A_s} = 0.7135 \ percent$$

The uncertainty calculation for the Fourier conduction term given below

$$\frac{\delta \Phi}{\Phi} = [(\frac{\delta q}{q})^2 + (\frac{\delta k_{cu}}{k_{cu}})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

k_{cu} was calcluated using

$$k_{cu} = 434.0 - [0.112(\overline{T}_{wi})]$$

$$k_{cu} = 434.0 - [0.112(283.25)]$$

$$k_{cu} = 402.28 \ W/mK$$

and its uncertainty

$$\delta k_{cu} = [(0.112(\delta \overline{T}_{wi}))^2]^{0.5}$$

δT_{wi} and $\delta Tsat$ are obtained using uncertainties in the thermocouple readings. Average wall inside temperature T_{wi} was obtained taking the average of six thermocouple readings inside the tube wall. The uncertainty associated with this variable is

$$\delta \overline{T}_{wi} = [6(\frac{\sum \delta T_{wi}}{6})^2]^{0.5}$$

where δT_{wi} for each thermocouple was obtained by taking the difference between the measured wall temperature and the average wall temperature. Using this method, it has been attempted to try and take into acount some the uncertainty introduced by the fabrication procedure for the tube (ie. air gap). For this particular heat flux the following δT_{wi} were found for tube thermocouples 1, 2, 3, 4, 5, and 6.

$$\delta \overline{T}_{wi} = [(\frac{0.37}{6})^2+(\frac{0.69}{6})^2+(\frac{0.29}{6})^2+(\frac{0.75}{6})^2+(\frac{0.21}{6})^2+(\frac{1.18}{6})^2]^{0.5}$$

$$\delta \overline{T}_{wi} = .274^\circ C$$

The uncertainty level for all remaining thermocouple readings (ie. excluding those in the tube wall which was considered to have a higher uncertainty) was estimated to be +/- 0.1 °C corresponding to an emf of approximately 4 μV. Saturation temperature was obtained by taking the average of two thermocouple readings and the uncertainty in this temperature was calculated from the following equation.

$$\delta Tsat = [2(\frac{\delta T_c}{2})^2]^{0.5}$$

$$\delta Tsat = [2(\frac{0.1}{2})^2]^{0.5}$$

$$\delta Tsat = 0.07^\circ C$$

Knowing the uncertainty in the temperatures, we can now calculate the uncertaines in the following:

$$\delta k_{cu} = [(0.112(\delta \overline{T}_{wi}))^2]^{0.5}$$

$$\delta k_{cu} = [(0.112(283.25))^2]^{0.5}$$

$$\delta k_{cu} = 31.724\ W/mK$$

Now we can calculate the uncertainty in the Fourier conduction term

$$\frac{\delta\phi}{\phi} = [(\frac{\delta q}{q})^2 + (\frac{\delta k_{cu}}{k_{cu}})^2 + (\frac{\delta L}{L})^2]^{0.5}$$

$$\frac{\delta\phi}{\phi} = [(0.0172)^2 + (\frac{31.724}{402.28})^2 + (\frac{0.2}{203.2})^2]^{0.5}$$

$$\frac{\delta\phi}{\phi} = 8.072\ percent$$

from the sample calculations we know that

$$\phi = 0.2679^\circ C \qquad \delta\phi = 0.2679(0.08072) = 0.0216^\circ C$$

therefore:

$$\frac{\delta h}{h} = [(\frac{\delta q}{q})^2 + (\frac{\delta A_s}{A_s})^2 + (\frac{\delta \overline{T}_{wi}}{\theta_b})^2 + (\frac{\delta\phi}{\theta_b})^2 + (\frac{\delta Tsat}{\theta_b})^2]^{0.5}$$

$$\frac{\delta h}{h} = [(0.0172)^2 + (0.07135)^2 + (\frac{0.04}{7.70})^2 + (\frac{0.0216}{7.70})^2 + (\frac{0.07}{7.70})^2]^{0.5}$$

$$\frac{\delta h}{h} = 7.42\ percent$$

Finally the calculation of wall superheat temperature

$$\theta_b = \overline{T}_{wo} - Tsat$$

$$\frac{\delta\theta_b}{\theta_b} = [(\frac{\delta \overline{T}_{wo}}{\theta_b})^2 + (\frac{\delta Tsat}{\theta_b})^2]^{0.5}$$

$$\frac{\delta\theta_b}{\theta_b} = [(\frac{0.274}{7.7})^2 + (\frac{.07}{7.7})^2]^{0.5}$$

$$\frac{\delta\theta_b}{\theta_b} = 3.67 \ percent$$

Table 4 shows the results of the uncertainty analysis performed. The high and low heat flux correspond to the approximate values of $7.5\text{x}10^4$ W/m^2 and $1\text{x}10^3$ W/m^2 respectively. Note that the highest uncertainty (over 50%) is in the wall superheat at very low heat flux (1 kW/m^2). This is due to the very low measured value of wall superheat (0.54 °C) which can not be accurately measured. Thus higher uncertainty occurs at very low heat fluxes. However, once the wall superheat gets higher (at higher heat fluxes) the uncertainty in wall superheat decreases significantly (to about 4%) indicative of the fact that the measure wall temperature is relatively more accurate.

Table 4. UNCERTAINTY ANALYSIS RESULTS

VARIABLE	HIGH HEAT FLUX	LOW HEAT FLUX
θ_b	7.7	0.54
$\overline{T}_{wi}$	10.25	2.80
T_{sat}	2.24	2.20
$\delta Vas/Vas$	1.57%	14.6%
$\delta Aas/Aas$	0.712%	7.9%
$\delta q/q$	1.72%	16.6%
$\delta D_o/D_o$	0.707%	0.707%
$\delta L/L$	0.098%	0.098%
$\delta A_s/A_s$	0.714%	0.714%
$\delta k_{cu}/k_{cu}$	7.89%	7.89%
$\delta\theta_b/\theta_b$	3.67%	52.37%
$\delta h/h$	7.42%	28.93%

APPENDIX D: OPERATING PROCEDURE

A. SYSTEM STARTUP

1. Power to the 28 kW (8 ton) refrigeration unit is provided by the breakers located in the main distribution panel located in the laboratory. These breakers were never secured. However, if power to this panel was lost, then these breakers must be reset.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position. This switch is always left on, unless unit was taken down for long repairs.

3. Push the start button in the control box for the recirculation pump. This control box is located on the bulkhead above the recirculation pump in the outside area adjacent to the refrigeration unit.

4. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately one hour to chill the sump to $-15\ ^{o}C$. The thermometer in the ethylene glycol/water mixture (sump) must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

5. Energize the desired pumps by switching on the breakers in the main distribution power panel. Once the power is energized in the main power panel and after ensuring the pump suction valves are open, turn on the

pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol/water sump. The pumps are marked "auxiliary condenser" (Pump #2) and "instrumented tube condenser" (Pump #1), respectively in the breaker box. Flow in the auxiliary condensate coils can be controlled with the individual globe valves located at the coil penetrations on the apparatus. The auxiliary condenser coils will produce the fastest adjustments to the system pressure.

6. Energize the heater variac(s) desired by switching on the breakers (Bundle, and Simulation (for test 7 only)) in the main distribution power panel and individual breakers for each of these in the power distribution box (near apparatus).

7. After ensuring that the breakers for the heated tubes desired are in the "on" position, follow the experimental procedures for normal operation outlined in Chapter IV.

B. SYSTEM SHUTDOWN

1. Turn all variacs to the zero position and switch off all breakers in the power panels.

2. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on".

3. Allow the recirculation pump to operate for at least five minutes after switching off the refrigeration pump unit to dissipate any back pressure in the system.

4. Turn the breakers for the pumps to the off position at the switch boxes, and then secure the power at the main distribution power panel.

C. EMERGENCY SHUTDOWN

1. Secure all power at the main distribution power panel

2. Evacuate building

3. Call Fire Department

APPENDIX E: PROGRAM DRP4RH

```
1000! FILE NAME  DRP4RH
1004! DATE       November 22, 1988
1008! REVISED    FEB 1992 (R. HAAS)
1012!
1016  BEEP
1020  PRINTER IS 1
1024  Idp=0
1028!
1032  PRINT USING "4X,""Select option default is 0."""
1036  PRINT USING "6X,""0 Taking data or re-processing previous data"""
1040  PRINT USING "6X,""1 Plotting data on Log-Log """
1044  PRINT USING "6X,""2 Plotting data on Linear"""
1048  PRINT USING "6X,""3 Purge"""
1052  PRINT USING "6X,""4 Fixup"""
1056  PRINT USING "6X,""5 Move"""
1060  PRINT USING "6X,""6 Comb"""
1064  PRINT USING "6X,""7 Read Plot"""
1068!
1072! IDP IS A PROGRAM VARIABLE TO SELECT A SUBROUTINE
1076  INPUT Idp
1080  IF Idp=0 THEN CALL Main
1084  IF Idp=1 THEN CALL Plot
1088  IF Idp=2 THEN CALL Plin
1092  IF Idp=3 THEN CALL Purg
1096  IF Idp=4 THEN CALL Fixup
1100  IF Idp=5 THEN CALL Move
1104  IF Idp=6 THEN CALL Comb
1108  IF Idp=7 THEN CALL Readplot
1112  END
1116!
1120  SUB Main
1124! ICAL=THERMOCOUPLE CALIBRATION
1128  COM /Cc/ C(7)
1132  DIM Emf(35),T(35),D1a(6),D2a(6),Dia(6),Doa(6),La(6),Lua(6),Kcua(6),Et(19),
Ldtc(20),Volt(2),Amp(11),Twa(5),Tw(5),Theta(5),Thetab(5),Q(5),Q1(5),Qdp(5)
1136  DIM Htube(5),Tn(5),Tp(6)
1140!
1144! THERMOCOUPLE ARRAY (C( )) INITIALIZATION
1148  DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1152  DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1156  READ C(*)
1160!
1164! PRINT HEADER AND INITIALIZE TIME CLOCK
1168  PRINTER IS 701
1172  BEEP
1176  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1180! OUTPUT DIRECTED TO DATA AQUISITION SYSTEM (HP 3497A)
1184  OUTPUT 709;"TD";Date$
1188  OUTPUT 709;"TD"
1192  ENTER 709;Date$
1196  PRINT
1200  PRINT "          Month, date and time :";Date$
1204  PRINT
1208  PRINT USING "10X,""NOTE  Program name   DRP4RH"""
1212  BEEP
1216!
1220! DN IS THE VARIABLE FOR DISC NUMBER FOR RECORD KEEPING ONLY
1224  INPUT "ENTER DISK NUMBER",Dn
1228  PRINT USING "16X,""Disk number  = "",ZZ",Dn
```

```
1232  BEEP
1236  Im=0
1240  INPUT "ENTER INPUT MODE (0=3497A,1=FILE) 0=DEFAULT",Im
1244!
1248! INPUT MODE ZERO IS FROM THE DATA AQUISITION SYSTEM
1252  IF Im=0 THEN
1256       BEEP
1260       INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2file$
1264       PRINT USING "16X,""File name  "",14A",D2file$
1268!
1272!      CREATE BDAT FILE ON THE MASS STORAGE MEDIA
1276       CREATE BDAT D2file$,60
1280!      CREATE AN INPUT/OUTPUT LINK TO OPEN FILES
1284       ASSIGN @File2 TO D2file$
1288!
1292!      CREATE DUMMY FILE UNTIL Nrun KNOWN
1296       D1file$="DUMMY"
1300       CREATE BDAT D1file$,60
1304       ASSIGN @File1 TO D1file$
1308       OUTPUT @File1;Date$
1312!
1316!      CREATE A PLOT FILE
1320       BEEP
1324       INPUT "GIVE A NAME FOR THE PLOT FILE",Pfile$
1328       CREATE BDAT Pfile$,30
1332       ASSIGN @Plot TO Pfile$
1336       BEEP
1340!
1344!      IDTC = NUMBER (TOTAL) OF DEFECTIVE THERMOCOUPLES
1348       INPUT "ENTER NUMBER OF DEFECTIVE TCS (0=DEFAULT)",Idtc
1352!      LDTC = LOCATION OF DEFECTIVE THERMOCOUPLE
1356!
1360       IF Idtc=0 THEN
1364            PRINT USING "16X,""No defective TCs exist"""
1368         ELSE
1372            PRINT USING "16X,""Defective Thermocouples Indicated by -99.99"""
1376       END IF
1380!
1384       BEEP
1388!      DEFECTIVE THERMOCOUPLES MAY BE IN CHANNELS 40-69
1392!      THEMOCOUPLES ARE ENTERED AS DEFECTIVE BY COMPUTER CHANNEL NO.
1396!      JDTC=COUNTER IN LOOP FOR DEFECTIVE THERMOCOUPLES
1400!
1404       IF Idtc>0 THEN
1408           FOR Jdtc=0 TO Idtc-1
1412              INPUT "ENTER DEFECTIVE TC LOCATION (BY COMPUTER CHANNEL NUMBER)
",Ldtc(Jdtc)
1416              BEEP
1420           NEXT Jdtc
1424       END IF
1428      PRINTER IS 701
1432      OUTPUT @File1;Ldtc(*)
1436 !
1440 !    Im=1 option (THIS OPTION ALLOWS DATA ENTRY WITH DATA FILE)
1444  ELSE
1448      BEEP
1452      INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D2file$
1456      PRINT USING "16X,""File name  "",14A";D2file$
1460      ASSIGN @File2 TO D2file$
1464      ENTER @File2,Nrun
```

```
1468      ENTER @File2;Dold$,Ldtc(*),Itt,Bop,Nht,Nato,Nrt,Corr
1472      BEEP
1476      INPUT "GIVE A NAME FOR PLOT FILE",Pfile$
1480      CREATE BDAT Pfile$,30
1484      ASSIGN @Plot TO Pfile$
1488      PRINT USING "16X,""This data set taken on   "",14A";Dold$
1492      BEEP
1496      PRINTER IS 1
1500      PRINT USING "4X,""SELECT TUBE TYPE"""
1504      PRINT USING "6X,""0 SMOOTH"""
1508      PRINT USING "5X,""1 FINNED(19/IN) """
1512      PRINT USING "6X,""2 HIGH FLUX """
1516      PRINT USING "6X,""3 TURBO-B """
1520      INPUT Itt
1524  END IF
1528  IF Im=1 THEN GOTO 1768
1532  PRINTER IS 1
1536!
1540  IF Im=0 THEN
1544       PRINT USING "4X,""Select tube type"""
1548       PRINT USING "6X,"" 0  Smooth """
1552       PRINT USING "6X,"" 1  FINNED 19/IN (DEFAULT)"""
1556       PRINT USING "6X,"" 2  HIGH FLUX"""
1560       PRINT USING "6X,"" 3  TURBO-B"""
1564       PRINT USING "6X,"" 4  GROWTH"""
1568       PRINT USING "6X,"" 5  GROWTH"""
1572       PRINT USING "6X,"" 6  GROWTH"""
1576!      ITT=TUBE TYPE
1580       INPUT Itt
1584       OUTPUT @File1;Itt
1588  END IF
1592  PRINTER IS 701
1596! Itt=2
1600  PRINT USING "16X,""Tube Type       "",DD";Itt
1604!
1608  BEEP
1612  Bop=0
1616  INPUT "ENTER BULK OIL %  (DEFAULT=0%) ",Bop
1620  OUTPUT @File1;Bop
1624  PRINT USING "16X,""Bulk oil%="",DD";Bop
1628!
1632  BEEP
1633  Ipo=1
1634  INPUT "ENTER POOL HEIGHT ABOVE TOP TUBE (0=LESS THEN 5cm, 1=5cm OR GREATER
 (DEFAULT)",Ipo
1635  OUTPUT @File1,Ipo
1636  PRINT USING "16X,""Pool height="",DD";Ipo
1637  BEEP
1639! NHT=NUMBER OF HEATED TUBES
1640  Nht=5
1644  INPUT "Enter number of heated instrumented tubes(default=5)",Nht
1648  OUTPUT @File1;Nht
1652  PRINT USING "16X,""Number of heated instrumented tubes="",DD",Nht
1653  BEEP
1655  Ipos=1
1656  IF Nht=1 THEN INPUT "WHICH POSITION IS THIS SINGLE TUBE (1 TO 5  DEF=1)",I
pos
1657  Ipos=Ipos-1
1658  BEEP
1660!
```

```
1664! Natp=Number of active dummy pairs
1668  Natp=0
1672  INPUT "Enter number of active dummy pairs (Default=0)",Natp
1676  OUTPUT @File1;Natp
1680  PRINT USING "16X,""Number of active dummy pairs=""",DD",Natp
1684  BEEP
1688!
1692! NRT=NUMBER OF ADDED HEATED TUBES TO ENHANCE BUNDLE EFFECT
1696  Nrt=0
1700  INPUT "Enter number of added heated tubes from simulation heaters(Default=
0)",Nrt
1704  OUTPUT @File1;Nrt
1708  PRINT USING "16X,""Number of added heated tubes(from simulation heaters)="
",DD";Nrt
1712  BEEP
1716!
1720! CORR IS CORRECTION FOR INSTRUMENTED TUBE HEIGHT
1724  Corr=0
1728  INPUT "WANT TO CORRECT TSAT FOR TUBE HEIGHT (0=YES(DEFAULT),1=NO)",Corr
1732        IF Corr=0 THEN PRINT USING "16X,""TSAT is corrected instrumented heat
ed tube height"""
1736        IF Corr=1 THEN PRINT USING "16X,""TSAT is NOT corrected for instrumen
ted heated tube height"""
1740  OUTPUT @File1;Corr
1744  BEEP
1748! ILQV=INPUT MODE: LIQUID, VAPOR,OR LIQUID VAPOR AVERAGE
1752  Ilqv=0
1756  INPUT "SELECT (0=LIQ(default),1=VAP,2=(LIQ+VAP)/2)",Ilqv
1760!
1764! D1A=Diameter at thermocouple positions (meters)
1768  DATA .0122,0.0098,0.0105,0.0116,0,0,0
1772  READ D1a(*)
1776  D1=D1a(Itt)
1780!
1784! D2=Diameter to base of fins (outside dia for smooth)(meters)
1788  DATA .0158,0.0125,0.0158,0.01415,0,0,0
1792  READ D2a(*)
1796  D2=D2a(Itt)
1800!
1804! Di=Inside diameter of unenhanced ends (meters)
1808  DATA .0132,0.0109,0.0116,0.0127,0,0,0
1812  READ Dia(*)
1816  Di=Dia(Itt)
1820!
1824! Do=Outside diameter of unenhanced ends (meters)
1828  DATA .015875,0.0125,0.015875,0.01415,0,0,0
1832  READ Doa(*)
1836  Do=Doa(Itt)
1840!
1844! L=Length of enhanced surface (meters)
1848  DATA .2032,.2032,.2032,.2032,.2032,.2032,.2032
1852  READ La(*)
1856  L=La(Itt)
1860!
1864! Lu=CORRECTED Length of unenhanced surface at the ends (METERS
1868!LU=LFIN + THICKNESS/2
1872  DATA .0261,.0254,.0264.0.0258,0,0,0
1876  READ Lua(*)
1880  Lu=Lua(Itt)
1884!
```

```
1888! Lv=corrected length of 2 inch finned like end
1892  DIM Lva(6)
1896  DATA .0769,.0762,.0772,0.0765,0,0,0
1900  READ Lva(*)
1904  Lv=Lva(Itt)
1908! Kcue=Thermal Conductivity of tube
1912! DATA 401,0,0,0,0,0,0
1916! READ Kcua(*)
1920! Kcu=Kcua(Itt)
1924  A=PI*(Do^2-Di^2)/4
1928  F=PI*Do
1932  J=1
1936  Sx=0
1940  Sy=0
1944  Sxs=0
1948  Sxy=0
1952 Repeat: !
1956!
1960  IF Im=0 THEN
1964!      Dtld=desired temperature of liquid
1968!      Dtld=47.5      !R-113
1969       Dtld=2.2       !R-114
1972       Ido=2
1976       ON KEY 0,15 RECOVER 1952
1980       PRINTER IS 1
1984       PRINT USING "4X,""SELECT OPTION """
1988       PRINT USING "6X,""0=TAKE DATA"""
1992       PRINT USING "6X,""1=SET HEAT FLUX"""
1996       PRINT USING "6X,""2=SET Tsat (DEFAULT SET FOR R-114)"""
2000       PRINT USING "4X,""NOTE: KEY 0 = ESCAPE"""
2004!      Ido=desired option
2008       BEEP
2012       INPUT Ido
2016!
2020       BEEP
2024!      Set default value for input
2028       IF Ido>2 THEN Ido=2
2032!      Take data option
2036       IF Ido=0 THEN 2440
2040!
2044! LOOP TO SET HEAT FLUX  (FOR TOP INSTRUMENTED TUBE)
2048       IF Ido=1 THEN
2052       Dqdp=100000
2056            PRINT USING "4X,""Qdp            QDPsim        Nrt       Qdpaux
  Qtot"""
2060            PRINT USING "4X,""(W/m^2)        (W/m^2)                  (W/m^2)
  (W)"""
2064            Err=1
2068!           Reset,read channel 25-30,automatic scaling
2072!           Channel 25=aux amps,26=sim amps,27=inst volts,28=sim volts,29=aux
 volts,30-34=inst amps
2076            OUTPUT 709;"AR AF25 AL34 VR5"
2080            FOR I=10 TO 11
2084                OUTPUT 709;"AS SA"
2088                ENTER 709;Amp(I)
2092            NEXT I
2096            FOR I=0 TO 2
2100                OUTPUT 709;"AS SA"
2104                ENTER 709;Volt(I)
2108            NEXT I
```

```
2108            FOR I=0 TO 4
2112            OUTPUT 709."AS SA"
2116            ENTER 709.Amp(I)
2117            NEXT I
2120!           Calculate actual heat flux
2124            Q(0)=60*Volt(0)*Amp(Ipos)
2128            Qdp(0)=Q(0)/(PI*D2*L)
2132            Qsim=60*20*Volt(1)*Amp(11)
2136            Qdpsim=Qsim/(PI*D2*.2032*3)
2140            Qaux=60*20*Volt(2)*Amp(10)
2144            Qdpaux=Qaux/(PI*.0160*.1778*4)
2148            Qtot=Q(0)*Nht+Qsim+Qaux
2152            Nrt=Qdpsim/Qdp(0)
2156            IF ABS(Aqdp-Oqdp)>Err THEN
2160                IF Aqdp>Dqdp THEN
2164                    BEEP 4000,.2
2168                ELSE
2172                    BEEP 250,.2
2176                END IF
2180                IF Nrt<.1 THEN Nrt=0
2184                IF Qdpaux<100 THEN Qdpaux=0
2188                IF Qdpsim<100 THEN Qdpsim=0
2192                PRINT USING "4X,2(MZ.3DE,2X),2X,(MDD.DD),2X,2(MZ.3DE,2X)";Qdp
(0),Qdpsim,Nrt,Qdpaux,Qtot
2196                WAIT 2
2200                GOTO 2076
2204            END IF
2208        END IF
2212!
2216!       LOOP TO SET Tsat
2220        IF Ido=2 THEN
2224            IF Ikdt=1 THEN 2240
2228                BEEP
2232!               INPUT "ENTER DESIRED Tsat (DEFAULT=47.5 C - R-113)",Dtld
2233                INPUT "ENTER DESIRED Tsat (DEFAULT=2.2 C - R-114)",Dtld
2236                Ikdt=1
2240                Oid1=0
2244                Oid2=0
2248                Nn=1
2252                Nrs=Nn MOD 15
2256                Nn=Nn+1
2260                IF Nrs=1 THEN
2264                    PRINT USING "4X,""  DTsat       Tld1       Tld2       Tlbb
    Tvat       Tvab       Tlav     """
2268                END IF
2272!               Read thermocouple voltages for vapor, liquid
2276                OUTPUT 709."AF AF0 AL5 VR5"
2280!               Sample each thermocouple 20 times and report temp for each the
rmocouple, vapor=0,1,2; liquid=3&4
2284                FOR I=0 TO 5
2288                    Sum=0
2292                    OUTPUT 709;"AS SA"
2296                    FOR Ji=1 TO 20
2300                        ENTER 709.Eliq
2304                        Sum=Sum+Eliq
2308                    NEXT Ji
2312                    Emf(I)=Sum/20
2316                    T(I)=FNTvsv(Emf(I))
2320                NEXT I
2324!           Compute average temperature of liquid
```

```
2328         Tlav=(T(3)+T(4))*.5
2332!        Compute average temperature of vapor
2333         Tvav1=(T(0)+T(1))/2
2334         Tvav2=T(2)
2336         Tvav=(T(0)+T(1)+T(2))/3
2340         IF ABS(Tlav-Otld)>.2 THEN
2344             IF Tlav>Otld THEN
2348                 BEEP 4000,.2
2352             ELSE
2356                 BEEP 250,.2
2360             END IF
2364         ELSE
2368             IF ABS(Tlav-Otld)>.1 THEN
2372                  IF Atld>Otld THEN
2376                       BEEP 3000,.2
2380                  ELSE
2384                       BEEP 800,.2
2388                  END IF
2392             END IF
2396         END IF
2400         Err1=Tlav-Old1
2404         Old1=Tlav
2408         Err2=Tvav-Old2
2412         Old2=Tvav
2416         PRINT USING "4X,7(MDDD.DD,3X)";Otld,T(3),T(4),T(5),Tvav1,Tvav2,Tla
v
2420         WAIT 2
2424         GOTO 2252
2428     END IF
2432!
2436!    TAKE DATA IF Im=0 LOOP
2440     IF Ikol=1 THEN 2452
2444         BEEP
2448         Ikol=1
2452         OUTPUT 709;"AR AF0 AL5 VR5"
2456         FOR I=0 TO 5
2460             OUTPUT 709;"AS SA"
2464             Sum=0
2468             FOR Ji=1 TO 20
2472                 ENTER 709;E
2476                 Sum=Sum+E
2480                 IF I>2 THEN Et(Ji-1)=E
2484             NEXT Ji
2488             Kdl=0
2492             IF I>2 THEN
2496                 Eave=Sum/20
2500                 Sum=0.
2504                 FOR Jk=0 TO 19
2508                     IF ABS(Et(Jk)-Eave)<5.0E-6 THEN
2512                          Sum=Sum+Et(Jk)
2516                     ELSE
2520                          Kdl=Kdl+1
2524                     END IF
2528                 NEXT Jk
2532                 IF I>2 THEN PRINT USING "4X,""Kdl = "",DD";Kdl
2536                     IF Kdl>10 THEN
2540                         BEEP
2544                         BEEP
2548                         PRINT USING "4X,""Too much scattering in data - re
peat data set"""
```

```
2552                     GOTO 1980
2556                 END IF
2560             END IF
2564         Emf(I)=Sum/(20-Kd1)
2568     NEXT I
2572     OUTPUT 709;"AR AF40 AL69 VR5"
2576     FOR I=6 TO 35
2580         OUTPUT 709;"AS SA"
2584         Sum=0
2588         FOR J1=1 TO 5
2592             ENTER 709;E
2596             Sum=Sum+E
2600         NEXT J1
2604         Emf(I)=Sum/5
2608     NEXT I
2612!
2616!    READ VOLTAGES (27=Inst,28=Sim,29=Aux)
2620     OUTPUT 709;"AR AF27 AL29 VR5"
2624     FOR I=0 TO 2
2628         OUTPUT 709;"AS SA"
2632         ENTER 709;Volt(I)
2636     NEXT I
2640!
2644!    READ CURRENTS (30-34=Inst tubes;35-39=ACTIVE Dummy)
2648     OUTPUT 709;"AR AF30 AL39 VR5"
2652     FOR I=0 TO 9
2656         OUTPUT 709;"AS SA"
2660         ENTER 709;Amp(I)
2664     NEXT I
2668! Read Currents(25=Aux amps,26=Sim amps)
2672     OUTPUT 709;"AR AF25 AL26 VR5"
2676     FOR I=10 TO 11
2680         OUTPUT 709;"AS SA"
2684         ENTER 709;Amp(I)
2688     NEXT I
2692     ELSE
2696     ENTER @File2;Emf(*),Volt(*),Amp(*)
2700 END IF
2704!
2708! CONVERT EMF'S TO TEMP,VOLT,CURRENT
2712 FOR I=0 TO 35
2716     T(I)=FNTvsv(Emf(I))
2720     IF I>5 AND Idtc>0 THEN
2724         FOR I1=0 TO Idtc-1
2728             IF Ldtc(I1)=I-5+39 THEN T(I)=-99.99
2732         NEXT I1
2736     END IF
2740 NEXT I
2744! Ntc=nr of thermocouples
2748 Ntc=6
2749 IF Ipos>0 THEN
2750     Q(Ipos)=60*Volt(0)*Amp(Ipos)
2751     Twa(Ipos)=0
2752     Jj=0
2754     Ndtc=0
2755     FOR I=1 TO Ntc
2756         Nn=Ipos*6+6+Jj
2757         Jj=Jj+1
2759         IF ABS(T(Nn))>99 THEN
2760            T(Nn)=-99.99
```

```
2761                Ndtc=Ndtc+1
2762             ELSE
2763                Twa(Ipos)=Twa(Ipos)+T(Nn)
2764             END IF
2765          NEXT I
2766          Twa(Ipos)=Twa(Ipos)/(6-Ndtc)
2767          GOTO 2820
2768      END IF
2769      FOR I1=0 TO 4
2770          Q(I1)=60*Volt(0)*Amp(I1)
2771!         Twa=Average temperature of the wall
2772          Twa(I1)=0
2773          Ndtc=0
2774          FOR I=1 TO Ntc
2776!             Nn is counter in temp array, start at 6 (this is the  first th
ermocouple in the tube bank)
2780              Nn=I1*6+I+5
2784              IF ABS(T(Nn))>99 THEN
2788                  T(Nn)=-99.99
2792                  Ndtc=Ndtc+1
2796              ELSE
2800                  Twa(I1)=Twa(I1)+T(Nn)
2804              END IF
2808          NEXT I
2812          Twa(I1)=Twa(I1)/(6-Ndtc)
2816      NEXT I1
2820      Tlav=(T(3)+T(4))/2
2821      Tvav=T(2)
2824!     Tvav=(T(0)+T(1)+T(2))/3
2828!
2829!     Tlav=T(5)
2832      Tcu=Twa(0)
2836      Kcu=FNKcu(Tcu)      !THERMAL CONDUCTIVITY OF COPPER
2840!                         !IF CURVE FIT NOT AVAIL USE ARRAY KCU(*)
2844! FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
2848      FOR I=0 TO 4
2852          Tw(I)=Twa(I)-Q(I)*LOG(D2/D1)/(2*PI*Kcu*L)
2856          IF Ilqv=0 THEN Texs=Tlav
2860          IF Ilqv=1 THEN Texs=Tvav
2864          IF Ilqv=2 THEN Texs=(Tlav+T(2))*.5
2868          IF Corr=1 THEN Thetab(I)=Tw(I)-Texs
2872          IF Corr=0 THEN Thetab(I)=Tw(I)-(Texs+.056+I*.129)  !R-114
2876!         IF Corr=0 AND Ipo=1 THEN Thetab(I)=Tw(I)-(Texs+.054+I*.144)  !R-11
3
2877!         IF Corr=0 AND Ipo=0 THEN Thetab(I)=Tw(I)-(Texs-1.078+.147*I)   !R-
113
2880      NEXT I
2884!
2888!     COMPUTE VARIOUS PROPERTIES
2892      Tfilm=(Tw(0)+Texs)*.5  !FILM TEMPERATURE
2896      Rho=FNRho(Tfilm)       !DENSITY
2900      Mu=FNMu(Tfilm)         !VISCOSITY
2904      K=FNK(Tfilm)           !THERMAL CONDUCTIVITY
2908      Cp=FNCp(Tfilm)         !SPECIFIC HEAT
2912      Beta=FNBeta(Tfilm)     !THERMAL EXPANSION
2916      Ni=Mu/Rho              !KINEMATIC VISCOSITY
2920      Alpha=K/(Rho*Cp)       !THERMAL DIFFUSIVITY
2924      Pr=Ni/Alpha            !PRANDTL
2928!
2932!     COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
```

```
2936!     FOF UNENHANCEC END(S)
2940      Lu=Lua(Itt)
2944      Hbar=190
2948      Fe=(Hbar*P/(Kcu*A))^.5*Lu
2952      Tanh=FNTanh(Fe)
2956      Theta(Ipos)=Thetab(Ipos)*Tanh/Fe
2960      Xx=(9.61*Beta*Thetab(Ipos)*Dc^3*Tanh/(Fe*Ni*Alpha))^.166667
2964      Yy=(1+(.559/Pr)^(9/16))^(8/27)
2968      Hbarc=K/Do*(.6+.387*Xx/Yy)^2
2972      IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
2976          Hbar=(Hbar+Hbarc)*.5
2980          GOTC 2948
2984      ENO IF
2988!
2992!     COMPUTE HEAT LDSS RATE THROUGH UNENHANCED END(S)
2996      Q1(0)=(Thetab(Ipos)*Tanh)*((Hbar*P*Kcu*A)^.5)
3000      Qq=Q1(0)+Qq
3004      Z=Z+1
3006      IF Z=1 THEN
3012         Lu=Lv
3016         GOTD 2944
3020      END IF
3024      Z=0
3028      Q1pct=Qq/Q(Ipos)
3032      Qq=0
3036      As=PI*D2*L
3040      FDR Ii=0 TD 4
3044          Q1(Ii)=Q1pct*Q(Ii)
3048          Qdp(Ii)=(Q(Ii)-Q1(Ii))/As
3052          Htube(Ii)=Qdp(Ii)/Thetab(Ii)
3056      NEXT Ii
3060      PRINTER IS 701
3064!
3068!     RECORD TIME DF DATA TAKING
3072      IF Im=0 THEN
3076          OUTPUT 709;"TD"
3080          ENTER 709;Told$
3084      END IF
3085!     CHURCHILL/CHU CORRELATION FOR NATURAL CONVECTION REGION
3087      Raa=9.81*Beta*Thetab(Ipos)*(D2)^3*Rho/(Mu*Alpha)
3088      Denom=(1.+(.559/Pr)^(9/16))^(16/9)
3089      Nuch=(.6+.387*(Raa/Denom)^(1/6))^2
3090      Qch=K*Nuch*Thetab(Ipos)/(D2)
3091!
3092!     OUTPUT DATA TO PRINTER
3096      PRINTER IS 701
3100      PRINT
3104      PRINT USING "10X,""Data Set Number = "",DDD,2X,14A";J,Told$
3108      PRINT
3112      PRINT USING "10X,""  Tv1      Tv2      Tv3      Tld1     Tld2     Tld3
Tvav    Tldav """
3116      PRINT USING "10X,8(MDD.DD,2X)";T(0),T(1),T(2),T(3),T(4),T(5),Tvav,Tlav
3120      PRINT
3124      PRINT USING "6X,""Tube    Wall Temperatures (Deg C)       Tnave      Qdp
   H        Thetab"""
3128      PRINT USING "6X,""#    1      2      3      4      5      6  (Deg C)  (W/m^
2)  (W/m^2.K)   (K)"""
3129      IF Ipos>0 THEN
3130         Jj=0
3132         FOR Ji=0 TO 5
```

```
3133          Tp(Ji)=T(Ipos*6+Jj+6)
3134          Jj=Jj+1
3136          NEXT Ji
3137          Inn=Ipos+1
3138          PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)";Inn,Tp(0
,Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(Ipos),Qdp(Ipos),Htube(Ipos),Thetab(Ipos)
3139          GOTO 3177
3140       END IF
3141       Jj=0
3142       FOR Ii=0 TO Nht-1
3143           FOR Ji=0 TO 5
3144               Tp(Ji)=T(Ii*5+Jj+6)
3148               Jj=Jj+1
3152           NEXT Ji
3156           Jj=Ii+1
3160           FOR Ji=0 TO 4
3164                Tn(Ji)=1+Ji
3168           NEXT Ji
3172           PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)";Tn(Ii),T
p(0),Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(Ii),Qdp(Ii),Htube(Ii),Thetab(Ii)
3176       NEXT Ii
3177       PRINT
3179       PRINT USING "6X,"" Heat Flux and Tdel from Churchill/Chu Correlation i
s "",1(MZ.3DE),2X,1(MDD.DD)";Qch,Thetab(Ipos)
3180       PRINT
3182       Dk=1
3184       IF Im=0 THEN
3188           BEEP
3192           INPUT "OK TO STORE THIS DATA SET (1=Y(default),0=N)?",Dk
3196       END IF
3200!      J=the counter for data sets
3204       IF Dk=1 OR Im=1 THEN J=J+1
3208       IF Dk=1 AND Im=0 THEN OUTPUT @File1;Emf(*),Volt(*),Amp(*)
3212       IF Im=1 OR Dk=1 THEN OUTPUT @Plot;Qdp(*),Htube(*),Thetab(*)
3216       Go_on=1
3220       IF Im=0 THEN
3224           BEEP
3228           INPUT "WILL THERE BE ANOTHER RUN (1=Y(default),0=N)?",Go_on
3232           Nrun=J
3236       IF Go_on=0 THEN 3272
3240       IF Go_on<>0 THEN Repeat
3244       ELSE
3248       IF J<Nrun+1 THEN Repeat
3252       END IF
3256       St=1
3260       BEEP
3264       INPUT "ARE YOU SURE YOUR READY TO TERMINATE (1=Y(DEFAULT),0=NO)?",St
3268       Go_on=1
3272       IF St>0 THEN 3280
3276       IF St=0 THEN GOTO 3240
3280       IF Im=0 THEN
3284           BEEP
3288           PRINT
3292           PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file ""
,10A";J-1,D2file$
3296           ASSIGN @File1 TO *
3300           OUTPUT @File2;Nrun-1
3304           ASSIGN @File1 TO D1file$
3308           ENTER @File1;Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
3312           OUTPUT @File2;Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
```

```
3316          FOR I=1 TO Nrun-1
3320              ENTER @File1;Emf(*),Volt(*),Amp(*)
3324              OUTPUT @File2;Emf(*),Volt(*),Amp(*)
3328          NEXT I
3332          ASSIGN @File1 TO *
3336          PURGE "DUMMY"
3340      END IF
3344      BEEP
3348      PRINT
3352      PRINT USING "10X,""NOTE  "",ZZ,"" X-Y pairs were stored in plot data f
ile "",10A";J-1,Pfile$
3356      ASSIGN @File2 TO *
3360      ASSIGN @Plot TO *
3364      BEEP
3368  SUBEND
3372!
3376!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3380!
3384  DEF FNKcu(Tcu)
3388! OFHC COPPER
3392  Tk=Tcu+273.15     !C TO K
3396  Kcu=434-.112*Tk      !250-300K USE FOR R-114 @2.2 C
3400! Kcu=433.0-.1*Tk      !200-400K USE FOR R-113 @47.5 C
3404  RETURN Kcu
3408  FNEND
3412!
3416  DEF FNMu(T)
3420! CURVE FIT OF VISCOSITY
3424  Tk=T+273.15      !C TO K
3428  Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3  !R-114 170-360 K
3432! Mu=.0000134*(10^(503/(Tk-2.15)))    !R113
3436  RETURN Mu
3440  FNEND
3444!
3448  DEF FNCp(T)
3452! CURVE FIT OF Cp
3456  Tk=T+273.15      !C TO K
3460  Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3 !R-114 180-400 K
3464! Cp=(925+1.03*T)*.001   !R-113
3468  Cp=Cp*1000
3472  RETURN Cp
3476  FNEND
3480!
3484  DEF FNRho(T)
3488  Tk=T+273.15      !C TO K
3492  X=1-(1.8*Tk/753.95)  !K TO R
3496  Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
3500  Ro=Ro/.062428       !R-114
3504! Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)     !R-113
3508  RETURN Ro
3512  FNEND
3516!
3520  DEF FNPr(T)    !GOOD FOR R-114/R-113
3524  Pr=FNCp(T)*FNMu(T)/FNK(T)
3528  RETURN Pr
3532  FNEND
3536!
3540  DEF FNK(T)
3544! T<360 K WITH T IN C
3548  K=.071-.000261*T
```

```
3552  RETURN F
3556  FNEND
3560!
3564  DEF FNTanh(Fe)
3568  P=EXP(Fe)
3572  Q=EXP(-Fe)
3576  Tanh=(P-Q)/(P+Q)
3580  RETURN Tanh
3584  FNEND
3588!
3592  DEF FNTvsv(V)
3596  COM /Cc/ C(7)
3600  T=C(0)
3604  FOR I=1 TO 7
3608  T=T+C(I)*V^I
3612  NEXT I
3616  RETURN T
3620  FNEND
3624!
3628  DEF FNBeta(T)
3632  Rop=FNRho(T+.1)
3636  Rom=FNRho(T-.1)
3640  Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
3644  RETURN Beta
3648  FNEND
3652  DEF FNPoly(X)
3656  COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
3660  X1=X
3664  Poly=B(0)
3668  FOR I=1 TO Nop
3672       IF Ilog=1 THEN X1=LOG(X)
3676       Poly=Poly+B(I)*X1^I
3680  NEXT I
3684  IF Ilog=1 THEN Poly=EXP(Poly)
3688  RETURN Poly
3692  FNEND
3696!
3700!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3704!
3708  SUB Poly(Ofile$(*),Np,Itn)
3712  DIM R(10),S(10),Sy(12),Sx(12),Xx(100),Yy(100),Xy(17)
3716  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
3720  COM /Xxyy/ Xp(5),Yp(5)
3724  FOR I=0 TO 4
3728  B(I)=0
3732  NEXT I
3736  Im=1
3740  BEEP
3744  INPUT "ENTER DATA FILE NAME",Dfile$(0)
3748  BEEP
3752  INPUT "ENTER NUMBER OF X-Y PAIRS",Np
3756  BEEP
3760  INPUT "LIKE TO EXCLUDE DATA PAIRS (1=Y,0=N(DEFAULT))?",Ied
3764  IF Ied=1 THEN
3768     BEEP
3772     INPUT "ENTER NUMBER OF PAIRS TO BE EXCLUDED",Ipex
3776  END IF
3780  ASSIGN @File TO Dfile$(0)
3784  N=3
3788  BEEP
```

```
3792  INPUT "ENTER THE ORDER OF POLYNOMIAL (DEFAULT=2  ",N
3796  FOR I=0 TO N
3800      Sy(I)=0
3804      Sx(I)=0
3808  NEXT I
3812  IF Ied=1 AND Im=1 THEN
3816     FOR I=1 TO Ipex
3820         ENTER @File;Xy(*)
3824     NEXT I
3828  END IF
3832  FOR I=1 TO Np-Ipex
3836      ENTER @File;Xy(*)
3840      IF Opo=0 THEN
3844         Y=Xy(Itn-1)
3848         X=Xy(11+Itn)
3852      END IF
3856      IF Opo=1 THEN
3860         Y=Xy(5+Itn)
3864         X=Xy(11+Itn)
3868      END IF
3872      IF Opo=2 THEN
3876         Y=Xy(5+Itn)
3880         X=Xy(Itn-1)
3884      END IF
3888      IF Ilog=1 THEN
3892         X=LOG(X)
3896         Y=LOG(Y)
3900      END IF
3904      Xx(I)=X
3908      Yy(I)=Y
3912      R(0)=Y
3916      Sy(0)=Sy(0)+Y
3920      S(1)=X
3924      Sx(1)=Sx(1)+X
3928      FOR J=1 TO N
3932          R(J)=R(J-1)*X
3936          Sy(J)=Sy(J)+R(J)
3940      NEXT J
3944      FOR J=2 TO N*2
3948          S(J)=S(J-1)*X
3952          Sx(J)=Sx(J)+S(J)
3956      NEXT J
3960  NEXT I
3964  Sx(0)=Np
3968  FOR I=0 TO N
3972      C(I)=Sy(I)
3976      FOR J=0 TO N
3980          A(I,J)=Sx(I+J)
3984      NEXT J
3988  NEXT I
3992  FOR I=0 TO N-1
3996      CALL Divide(I)
4000      CALL Subtract(I+1)
4004  NEXT I
4008  B(N)=C(N)/A(N,N)
4012  FOR I=0 TO N-1
4016      B(N-1-I)=C(N-1-I)
4020      FOR J=0 TO I
4024          B(N-1-I)=B(N-1-I)-A(N-1-I,N-J)*B(N-J)
4028      NEXT J
```

```
4032        B(N-1-I)=B(N-1-I)/A(N-1-I,N-1-I)
4036    NEXT I
4040    IF Iprnt=0 THEN
4044       PRINT USING "12X,""EXPONENT     COEFFICIENT"""
4048       FOR I=0 TO N
4052           PRINT USING "15X,DD,5X,MD.7DE",I,B(I)
4056       NEXT I
4060       PRINT " "
4064       PRINT USING "12X,""DATA POINT       X                 Y        Y(CALCULATED) DI
SCREPANCY"""
4068       FOR I=1 TO Np
4072           Yc=B(0)
4076           FOR J=1 TO N
4080               Yc=Yc+B(J)*Xx(I)^J
4084           NEXT J
4088           D=Yy(I)-Yc
4092           PRINT USING "15X,3D,4X,4(MD.5DE,1X)",I,Xx(I),Yy(I),Yc,D
4096       NEXT I
4100    END IF
4104    ASSIGN @File TO *
4108    SUBEND
4112!
4116    SUB Divide(M)
4120    COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4124    FOR I=M TO N
4128       Ao=A(I,M)
4132       FOR J=M TO N
4136           A(I,J)=A(I,J)/Ao
4140       NEXT J
4144       C(I)=C(I)/Ao
4148    NEXT I
4152    SUBEND
4156!
4160    SUB Subtract(K)
4164    COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4168    FOR I=K TO N
4172       FOR J=K-1 TO N
4176           A(I,J)=A(K-1,J)-A(I,J)
4180       NEXT J
4184       C(I)=C(K-1)-C(I)
4188    NEXT I
4192    SUBEND
4196!
4200    SUB Plin
4204    COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4208    COM /Xxyy/ Xx(5),Yy(5)
4212    PRINTER IS 705
4216    BEEP
4220    INPUT "SELECT (0=h/h0% same tube,1=h(HF)/h(sm)",Irt
4224    BEEP
4228    INPUT "WHICH Tsat (1=6.7,0=-2.2)",Isat
4232    Xmin=0
4236    Xmax=10
4240    Xstep=2
4244    IF Irt=0 THEN
4248       Ymin=0
4252       Ymax=1.4
4256       Ystep=.2
4260       ELSE
4264       Ymin=0
```

```
4268     Ymax=15
4272     Ystep=5
4276  END IF
4280  BEEP
4284  PRINT "IN;SP1.IP 2300,2200,8300,6800."
4288  PRINT "SC 0,100,0,100.TL 2,0."
4292  Sfx=100/(Xmax-Xmin)
4296  Sfy=100/(Ymax-Ymin)
4300  PRINT "PU 0,0 PD"
4304  FOR Xa=Xmin TO Xmax STEP Xstep
4308      X=(Xa-Xmin)*Sfx
4312      PRINT "PA";X,",0, XT;"
4316  NEXT Xa
4320  PRINT "PA 100,0;PU;"
4324  PRINT "PU PA 0,0 PD"
4328  FOR Ya=Ymin TO Ymax STEP Ystep
4332      Y=(Ya-Ymin)*Sfy
4336      PRINT "PA 0,";Y,"YT"
4340  NEXT Ya
4344  PRINT "PA 0,100 TL 0 2"
4348  FOR Xa=Xmin TO Xmax STEP Xstep
4352      X=(Xa-Xmin)*Sfx
4356      PRINT "PA";X,",100; XT"
4360  NEXT Xa
4364  PRINT "PA 100,100 PU PA 100,0 PD"
4368  FOR Ya=Ymin TO Ymax STEP Ystep
4372      Y=(Ya-Ymin)*Sfy
4376      PRINT "PD PA 100,",Y,"YT"
4380  NEXT Ya
4384  PRINT "PA 100,100 PU"
4388  PRINT "PA 0,-2 SR 1.5,2"
4392  FOR Xa=Xmin TO Xmax STEP Xstep
4396      X=(Xa-Xmin)*Sfx
4400      PRINT "PA";X,",0;"
4404      PRINT "CP -2,-1.LB";Xa;""
4408  NEXT Xa
4412  PRINT "PU PA 0,0"
4416  FOR Ya=Ymin TO Ymax STEP Ystep
4420      IF ABS(Ya)<1.E-5 THEN Ya=0
4424      Y=(Ya-Ymin)*Sfy
4428      PRINT "PA 0,";Y,""
4432      PRINT "CP -4,-.25;LB";Ya;""
4436  NEXT Ya
4440  Xlabel$="Oil Percent"
4444  IF Irt=0 THEN
4448     Ylabel$="h/h0%"
4452     ELSE
4456     Ylabel$="h/hsmooth"
4460  END IF
4464  PRINT "SR 1.5,2;PU PA 50,-10 CP".-LEN(Xlabel$)/2."0;LB";Xlabel$;""
4468  PRINT "PA -11,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$,""
4472  PRINT "CP 0,0"
4476  Ipn=0
4480  BEEP
4484  INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Olp
4488  Icn=0
4492  IF Olp=1 THEN
4496  BEEP
4500  INPUT "ENTER THE NAME OF THE DATA FILE",D_file$
4504  BEEP
```

```
4508  INPUT "SELECT (0=LINEAR, 1=LOG(X,Y))",Ilog
4512  ASSIGN @File TO D_file$
4516  BEEP
4520  INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4524  BEEP
4528  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Npairs
4532  BEEP
4536  INPUT "ENTER DESIRED HEAT FLUX",Q
4540  BEEP
4544  PRINTER IS 1
4548  PRINT USING "4X,""Select a symbol """
4552  PRINT USING "4X,""1  Star   2  Plus sign"""
4556  PRINT USING "4X,""3  Circle 4  Square"""
4560  PRINT USING "4X,""5  Rombus"""
4564  PRINT USING "4X,""6  Right-side-up triangle"""
4568  PRINT USING "4X,""7  Up-side-down triangle"""
4572  INPUT Sym
4576  PRINTER IS 705
4580  PRINT "PU DI"
4584  IF Sym=1 THEN PRINT "SM*"
4588  IF Sym=2 THEN PRINT "SM+"
4592  IF Sym=3 THEN PRINT "SMo"
4596  Nn=4
4600  IF Ilog=1 THEN Nn=1
4604  IF Md>1 THEN
4608     FOR I=1 TO (Md-1)
4612         ENTER @File,Xa,Ya
4616     NEXT I
4620  END IF
4624  Q1=Q
4628  IF Ilog=1 THEN Q=LOG(Q)
4632  FOR I=1 TO Npairs
4636      ENTER @File;Xa,B(*)
4640      Ya=B(0)
4644      FOR K=1 TO Nn
4648          Ya=Ya+B(K)*Q^K
4652      NEXT K
4656      IF Ilog=1 THEN Ya=EXP(Ya)
4660      IF Ilog=0 THEN Ya=Q1/Ya
4664      IF Irt=0 THEN
4668         IF Xa=0 THEN
4672            Yo=Ya
4676            Ya=1
4680            ELSE
4684            Ya=Ya/Yo
4688         END IF
4692         ELSE
4696         Hsm=FNHsmooth(Q,Xa,Isat)
4700         Ya=Ya/Hsm
4704      END IF
4708  Xx(I-1)=Xa
4712  Yy(I-1)=Ya
4716  X=(Xa-Xmin)*Sfx
4720  Y=(Ya-Ymin)*Sfy
4724  IF Sym<3 THEN PRINT "SM"
4728  IF Sym>4 THEN PRINT "SR 1.4,2.4"
4732  PRINT "PA",X,Y,""
4736  IF Sym>3 THEN PRINT "SR 1.2,1.6"
4740  IF Sym=4 THEN PRINT "UC2.4,99,0,-8,-4,0,0,8,4,0,."
4744  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6,"
```

```
4748  IF Sym=6 THEN PRINT "UC0,5,3,99,3,-8,-6,0,3,8;"
4752  IF Sym=7 THEN PRINT "UC0,-5,3,99,-3,8,6,0,-3,-8;"
4756  NEXT I
4760  BEEP
4764  ASSIGN @File TO *
4768  END IF
4772  PRINT "PU SM"
4776  BEEP
4780  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y,0=N)?",Olp
4784  IF Olp=1 THEN
4788     BEEP
4792     INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
4796     Iprnt=1
4800     CALL Poly(Itn)
4804     FOR Xa=Xmin TO Xmax STEP Xstep/25
4808         Icn=Icn+1
4812         Ya=FNPoly(Xa)
4816         Y=(Ya-Ymin)*Sfy
4820         X=(Xa-Xmin)*Sfx
4824         IF Y<0 THEN Y=0
4828         IF Y>100 THEN GOTO 4868
4832         Pu=0
4836         IF Ipn=1 THEN Idf=Icn MOD 2
4840         IF Ipn=2 THEN Idf=Icn MOD 4
4844         IF Ipn=3 THEN Idf=Icn MOD 8
4848         IF Ipn=4 THEN Idf=Icn MOD 16
4852         IF Ipn=5 THEN Idf=Icn MOD 32
4856         IF Idf=1 THEN Pu=1
4860         IF Pu=0 THEN PRINT "PA",X,Y,"PD"
4864         IF Pu=1 THEN PRINT "PA",X,Y,"PU"
4868     NEXT Xa
4872     PRINT "PU"
4876     Ipn=Ipn+1
4880     GOTO 4480
4884  END IF
4888  BEEP
4892  INPUT "WANT TO QUIT (1=Y,0=N)?",Iquit
4896  IF Iquit=1 THEN 4904
4900  GOTO 4480
4904  PRINT "PU SP0"
4908  SUBEND
4912  SUB Stats
4916  PRINTER IS 701
4920  J=0
4924  K=0
4928  BEEP
4932  INPUT "PLOT FILE TO ANALYZE?",File$
4936  ASSIGN @File TO File$
4940  BEEP
4944  INPUT "LAST RUN No?(0=QUIT)",Nn
4948  IF Nn=0 THEN 5092
4952  Nn=Nn-J
4956  Sx=0
4960  Sy=0
4964  Sz=0
4968  Sxs=0
4972  Sys=0
4976  Szs=0
4980  FOR I=1 TO Nn
4984  J=J+1
```

```
4988  ENTER @File,Q,T
4992  H=Q/T
4996  Sx=Sx+Q
5000  Sxs=Sxs+Q^2
5004  Sy=Sy+T
5008  Sys=Sys+T^2
5012  Sz=Sz+H
5016  Szs=Szs+H^2
5020  NEXT I
5024  Qave=Sx/Nn
5028  Tave=Sy/Nn
5032  Have=Sz/Nn
5036  Sdevq=SQR(ABS((Nn*Sxs-Sx^2)/(Nn*(Nn-1))))
5040  Sdevt=SQR(ABS((Nn*Sys-Sy^2)/(Nn*(Nn-1))))
5044  Sdevh=SQR(ABS((Nn*Szs-Sz^2)/(Nn*(Nn-1))))
5048  Sh=100*Sdevh/Have
5052  Sq=100*Sdevq/Qave
5056  St=100*Sdevt/Tave
5060  IF K=1 THEN 5084
5064  PRINT
5068  PRINT USING "11X,""DATA FILE "",14A";File$
5072  PRINT
5076  PRINT USING "11X,""RUN Htube      SdevH   Qdp          SdevQ   Thetab SdevT""
"
5080  K=1
5084  PRINT USING "11X,DD,2(2X,D.3DE,1X,3D.2D),2X,DD.3D,1X,3D.2D";J,Have,Sh,Qave
,Sq,Tave,St
5088  GOTO 4940
5092  ASSIGN @File1 TO *
5096  PRINTER IS 1
5100  SUBEND
5104  SUB Coef
5108  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opc,Ilog
5112  BEEP
5116  INPUT "GIVE A NAME FOR CROSS-PLOT FILE",Cpf$
5120  BEEP
5124  INPUT "OUTPUT TYPE (0=q vs Dt, 1=h vs Dt, 2=h vs q)",Opc
5128  CREATE BDAT Cpf$,6
5132  ASSIGN @File TO Cpf$
5136  BEEP
5140  INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
5144  BEEP
5148  INPUT "ENTER OIL PERCENT (-1=STOP)",Bop
5152  BEEP
5156  INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5160  IF Bop<0 THEN 5176
5164  CALL Poly(Itn)
5168  OUTPUT @File,Bop,B(*)
5172  GOTO 5144
5176  ASSIGN @File TO *
5180  SUBEND
5184!
5188!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5192!
5196  SUB Plot
5200  COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opc,Ilog
5204  DIM Xy(17)
5208  INTEGER Ii
5212  PRINTER IS 1
5216  BEEP
```

```
5220  Idv=1
5224  INPUT "LIKE DEFAULT VALUES FOR PLOT (1=Y(DEFAULT),0=N ?",Idv
5228  Opo=0
5232  BEEP
5236  PRINT USING "4X,""Select Option """
5240  PRINT USING "6X,""0  q versus delta-T(DEFAULT)"""
5244  PRINT USING "6X,""1  h versus delta-T"""
5248  PRINT USING "6X,""2  h versus q"""
5252  INPUT Opo
5256  BEEP
5260  INPUT "SELECT UNITS (0=SI(DEFAULT),1=ENGLISH)",Iun
5264  PRINTER IS 705
5268  IF Idv<>1 THEN
5272     BEEP
5276     INPUT "ENTER NUMBER OF CYCLES FOR X-AXIS",Cx
5280     BEEP
5284     INPUT "ENTER NUMBER OF CYCLES FOR Y-AXIS",Cy
5288     BEEP
5292     INPUT "ENTER MIN X-VALUE (MULTIPLE OF 10)",Xmin
5296     BEEP
5300     INPUT "ENTER MIN Y-VALUE (MULTIPLE OF 10)",Ymin
5304  ELSE
5308     IF Opo=0 THEN
5312        Cy=2
5316        Cx=2
5320        Xmin=1
5324        Ymin=1000
5328     END IF
5332     IF Opo=1 THEN
5336        Cy=2
5340        Cx=2
5344        Xmin=1
5348        Ymin=100
5352     END IF
5356     IF Opo=2 THEN
5360        Cy=2
5364        Cx=2
5368        Xmin=1000
5372        Ymin=100
5376     END IF
5380  END IF
5384  BEEP
5388  PRINT "IN;SP1;IP 2300,2200,8300,6800."
5392  PRINT "SC 0,100,0,100;TL 2,0;"
5396  Sfx=100/Cx
5400  Sfy=100/Cy
5404  BEEP
5408  INPUT "WANT TO BY-PASS CAGE (1=Y, 0=NO(DEFAULT)",Ibp
5412  IF Ibp=1 THEN 5908
5416  PRINT "PU 0,0 PD"
5420  Nn=9
5424  FOR I=1 TO Cx+1
5428       Xat=Xmin*10^(I-1)
5432       IF I=Cx+1 THEN Nn=1
5436       FOR J=1 TO Nn
5440            IF J=1 THEN PRINT "TL 2 0"
5444            IF J=2 THEN PRINT "TL 1 0"
5448            Xa=Xat*J
5452            X=LGT(Xa/Xmin)*Sfx
5456            PRINT "PA",X,",0. XT."
```

```
5460      NEXT J
5464  NEXT I
5468  PRINT "PA 100,0,PU;"
5472  PRINT "PU PA 0,0 PD"
5476  Nn=9
5480  FOR I=1 TO Cy+1
5484      Yat=Ymin*10^(I-1)
5488      IF I=Cy+1 THEN Nn=1
5492      FOR J=1 TO Nn
5496          IF J=1 THEN PRINT "TL 2 0"
5500          IF J=2 THEN PRINT "TL 1 0"
5504          Ya=Yat*J
5508          Y=LGT(Ya/Ymin)*Sfy
5512          PRINT "PA 0,";Y,"YT"
5516      NEXT J
5520  NEXT I
5524  PRINT "PA 0,100 TL 0 2"
5528  Nn=9
5532  FOR I=1 TO Cx+1
5536      Xat=Xmin*10^(I-1)
5540      IF I=Cx+1 THEN Nn=1
5544      FOR J=1 TO Nn
5548          IF J=1 THEN PRINT "TL 0 2"
5552          IF J>1 THEN PRINT "TL 0 1"
5556          Xa=Xat*J
5560          X=LGT(Xa/Xmin)*Sfx
5564          PRINT "PA";X,",100; XT"
5568       NEXT J
5572  NEXT I
5576  PRINT "PA 100,100 PU PA 100,0 PD"
5580  Nn=9
5584  FOR I=1 TO Cy+1
5588      Yat=Ymin*10^(I-1)
5592      IF I=Cy+1 THEN Nn=1
5596      FOR J=1 TO Nn
5600          IF J=1 THEN PRINT "TL 0 2"
5604          IF J>1 THEN PRINT "TL 0 1"
5608          Ya=Yat*J
5612          Y=LGT(Ya/Ymin)*Sfy
5616          PRINT "PD PA 100,",Y,"YT"
5620      NEXT J
5624  NEXT I
5628  PRINT "PA 100,100 PU"
5632  PRINT "PA 0,-2 SR 1.5,2"
5636  I1=LGT(Xmin)
5640  FOR I=1 TO Cx+1
5644      Xa=Xmin*10^(I-1)
5648      X=LGT(Xa/Xmin)*Sfx
5652      PRINT "PA";X,",0."
5656      IF I1>=0 THEN PRINT "CP -2,-2;LB10.PR -2,2;LB";I1;""
5660      IF I1<0 THEN PRINT "CP -2,-2;LB10;PR 0,2;LB";I1;""
5664      I1=I1+1
5668  NEXT I
5672  PRINT "PU PA 0,0"
5676  I1=LGT(Ymin)
5680  Y10=10
5684  FOR I=1 TO Cy+1
5688      Ya=Ymin*10^(I-1)
5692      Y=LGT(Ya/Ymin)*Sfy
5696      PRINT "PA 0,";Y,""
```

```
5700        PRINT "CP -4,-.25.LB10.PR -2,2.LB",I1,""
5704        I1=I1+1
5708   NEXT I
5712   BEEP
5716   Idl=1
5720   INPUT "WANT USE DEFAULT LABELS (1=Y(DEFAULT),0=N)?",Idl
5724   IF Idl<>1 THEN
5728      BEEP
5732      INPUT "ENTER X-LABEL",Xlabel$
5736      BEEP
5740      INPUT "ENTER Y-LABEL",Ylabel$
5744   END IF
5746   IF Opo<2 THEN
5752      PRINT "SR 1,2.PU PA 40,-14;"
5756      PRINT "LB(T;PR -1.6,3 PD PR 1.2,0 PU;PR .5,-4.LBwo;PR .5,1;"
5760      PRINT "LB-T;PR .5,-1;LBsat;PR .5,1."
5764      IF Iun=0 THEN
5768         PRINT "LB) / (K)"
5772      ELSE
5776         PRINT "LB) / (F)"
5780      END IF
5784   END IF
5788   IF Opo=2 THEN
5792      IF Iun=0 THEN
5796         PRINT "SR 1.5,2;PU PA 40,-14;LBq / (W/m;SR 1,1.5;PR 0.5,1;LB2;SR 1
.5,2;PR 0.5,-1.LB)"
5800      ELSE
5804         PRINT "SR 1.5,2;PU PA 34,-14;LBq / (Btu/hr;PR .5,.5;LB.;PR .5,-.5;
"
5808         PRINT "LBft;PR .5,1;SR 1,1.5;LB2;SR 1.5,2;PR .5,-1;LB)."
5812      END IF
5816   END IF
5820   IF Opo=0 THEN
5824      IF Iun=0 THEN
5828         PRINT "SR 1.5,2;PU PA -12,40;DI 0,1;LBq / (W/m.PR -1,0.5;SR 1,1.5;L
B2.SR 1.5,2;PR 1,.5;LB)"
5832      ELSE
5836         PRINT "SR 1.5,2;PU PA -12,32.DI 0,1;LBq / (Btu/hr;PR -.5,.5;LB..PR
 .5,.5."
5840         PRINT "LBft;SR 1,1.5;PR -1,.5;LB2;PR 1,.5;SR 1.5,2;LB)"
5844      END IF
5848   END IF
5852   IF Opo>0 THEN
5856      IF Iun=0 THEN
5860         PRINT "SP 1.5,2;PU PA -12,38;DI 0,1.LBh / (W/m;PR -1,.5.SR 1,1.5.LB
2.SP 1.5,2.PR .5,.5;"
5864         PRINT "LB..PR .5,0.LBK)"
5868      ELSE
5872         PRINT "SR 1.5,2;PU PA -12,28;DI 0,1.LBh / (Btu/hr;PR -.5,.5;LB.;PR
 .5,.5;"
5876         PRINT "LBft;PR -1,.5.SR 1,1.5;LB2;SR 1.5,2;PR .5,.5;LB..PR .5,.5;
LBF)"
5880      END IF
5884   END IF
5888   IF Idl=0 THEN
5892      PRINT "SR 1.5,2.PU PA 50,-16 CP",-LEN(Xlabel$)/2,"0.LB";Xlabel$,""
5896      PRINT "PA -14,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$,""
5900      PRINT "CP 0,0 DI"
5904   END IF
5908   Ipn=0
```

```
5912 Repeat !
5916  X11=1.E+6
5920  Xul=-1.E+6
5924  Icn=0
5928  BEEP
5932  Ok=1
5936  INPUT "WANT TO PLOT DATA FROM A FILE (1=Y(DEFAULT),0=N)?",Ok
5940  IF Ok=1 THEN
5944  BEEP
5948  INPUT "ENTER THE NAME OF THE DATA FILE",Dfile$(0)
5952  ASSIGN @File TO Dfile$(0)
5956  BEEP
5960  Npairs=20
5964  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED(DEFAULT=20)",Npairs
5968  BEEP
5972  Itn=Itn+1
5976  INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5980  BEEP
5984  PRINTER IS 1
5988  INPUT "WANT DEFAULT SYMBOLS? (YES=0 (DEFAULT),NO=1)",Symb
5992  Sym=Itn+2
5996  IF Symb=0 THEN
6000     GOTO 6036
6004  END IF
6008  PRINT USING "4X,""Select a symbol:"""
6012  PRINT USING "6X,""1  Star      2  Plus sign"""
6016  PRINT USING "6X,""3  Circle    4  Square"""
6020  PRINT USING "6X,""5  Rombus"""
6024  PRINT USING "6X,""6  Right-side-up triangle"""
6028  PRINT USING "6X,""7  Up-side-down triangle"""
6032  INPUT Sym
6036  PRINTER IS 705
6040  PRINT "PU DI"
6044  IF Sym=1 THEN PRINT "SM*"
6048  IF Sym=2 THEN PRINT "SM+"
6052  IF Sym=3 THEN PRINT "SMo"
6056  FOR I=1 TO Npairs
6060  ENTER @File;Xy(*)
6064  IF Opo=0 THEN
6068     Ya=Xy(Itn-1)
6072     Xa=Xy(11+Itn)
6077  END IF
6080  IF Opo=1 THEN
6084     Ya=Xy(5+Itn)
6088     Xa=Xy(11+Itn)
6092  END IF
6096  IF Opo=2 THEN
6100     Ya=Xy(5+Itn)
6104     Xa=Xy(Itn-1)
6108  END IF
6112  IF Xa<X11 THEN X11=Xa
6116  IF Xa>Xul THEN Xul=Xa
6120  IF Iun=1 THEN
6124     IF Opo<2 THEN Xa=Xa*1.6
6128     IF Opo>0 THEN Ya=Ya*.1761
6132     IF Opo=0 THEN Ya=Ya*.317
6136     IF Opo=2 THEN Xa=Xa*.317
6140  END IF
6144  X=LGT(Xa/Xmin)*Sfx
6148  Y=LGT(Ya/Ymin)*Sfy
```

```
6152  Kj=0
6156  CALL Symb(X,Y,Sym,Icl,Kj)
6160  GOTO 6212
6164  IF Sym>3 THEN PRINT "SM"
6168  IF Sym<4 THEN PRINT "SR 1.4,2.4"
6172  IF Icl=0 THEN
6176     PRINT "PA",X,Y,""
6180  ELSE
6184     PRINT "PA",X,Y,"PD"
6188  END IF
6192  IF Sym>3 THEN PRINT "SR 1.2,1.6"
6196  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
6200  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
6204  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,6;"
6208  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
6212  NEXT I
6216  PRINT "PU"
6220  BEEP
6224  Ilab=1
6228  INPUT "WANT TO LABEL? (1=Y(DEFAULT),0=N)",Ilab
6232  IF Ilab=1 THEN
6236     PRINT "SP0.SP2"
6240     BEEP
6244     IF Klab=0 THEN
6248        Xlab=65
6252        Ylab=85
6256        INPUT "ENTER INITIAL X,Y LOCATIONS",Xlab,Ylab
6260        Xtt=Xlab-5
6264        Ytt=Ylab+8
6268        PRINT "SR 1,1.5"
6272        PRINT "SM;PA",Xtt,Ytt,"LB      Tube    %    File"
6276        Ytt=Ytt-3
6280        PRINT "PA",Xtt,Ytt,"LB       No    Oil   Name"
6284        IF Sym=1 THEN PRINT "SM*"
6288        IF Sym=2 THEN PRINT "SM+"
6292        IF Sym=3 THEN PRINT "SMo"
6296        Klab=1
6300     END IF
6304     Kj=1
6308     CALL Symb(Xlab,Ylab,Sym,Icl,Kj)
6312     PPINT "SR 1,1.5;SM"
6316     IF Sym<4 THEN PRINT "PR 2,0"
6320     PRINT "PR 2,0;LB",Itn;""
6324     BEEP
6328     INPUT "ENTER BOP(0=DEFAULT)",Bop
6332     IF Bop<10 THEN PRINT "PR 3,0;LB";Bop;""
6336     IF Bop>9 THEN PRINT "PR 1.5,0;LB";Bop;""
6340     PRINT "PR 2,0;LB";Dfile$(0);""
6344     PRINT "SP0.SP1;SR 1.5,2"
6348     Ylab=Ylab-5
6352  END IF
6356  BEEP
6360  ASSIGN @File TO *
6364  Xll=Xll/1.2
6366  Xul=Xul*1.2
6372 ! GOTO 8040
6376  END IF
6380  PRINT "PU SM"
6384  BEEP
6388  Go_on=1
```

```
6392  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y(DEFAULT),0=N)?",Gc_on
6396  IF Gc_on=1 THEN
6400     BEEP
6404     PRINTER IS 1
6408     INPUT "WANT DEFAULT LINE TYPE? (YES=0 (DEFAULT),NO=1)",Ln
6412     Ipn=Itn
6416     IF Ln=0 THEN
6420        GOTO 6448
6424     END IF
6428     PRINT USING "4X,""Select line type """
6432     PRINT USING "6X,""0      Solid line"""
6436     PRINT USING "6X,""1      Dashed"""
6440     PRINT USING "6X,""2,,,5 Longer line - dash"""
6444     INPUT Ipn
6448     PRINTER IS 705
6452     BEEP
6456     Ilog=1
6460     INPUT "SELECT (0=LIN,1=LOG(DEFAULT))",Ilog
6464     Iprnt=1
6468     CALL Poly(Dfile$(*),Npairs,Itn)
6472     FOR Xx=0 TO Cx STEP Cx/200
6476         Xa=Xmin*10^Xx
6480         IF Xa<Xll OR Xa>Xul THEN 6572
6484         Icn=Icn+1
6488         Pu=0
6492         IF Ipn=1 THEN Idf=Icn MOD 2
6496         IF Ipn=2 THEN Idf=Icn MOD 4
6500         IF Ipn=3 THEN Idf=Icn MOD 8
6504         IF Ipn=4 THEN Idf=Icn MOD 16
6508         IF Ipn=5 THEN Idf=Icn MOD 28
6512         IF Idf=1 THEN Pu=1
6516         Ya=FNPoly(Xa)
6520         IF Ya<Ymin THEN 6572
6524         IF Iun=1 THEN
6528            IF Opo<2 THEN Xa=Xa*1.8
6532            IF Opo>0 THEN Ya=Ya*.1761
6536            IF Opo=0 THEN Ya=Ya*.317
6540            IF Opo=2 THEN Xa=Xa*.317
6544         END IF
6548         Y=LGT(Ya/Ymin)*Sfy
6552         X=LGT(Xa/Xmin)*Sfx
6556         IF Y<0 THEN Y=0
6560         IF Y>100 THEN GOTO 6572
6564         IF Pu=0 THEN PRINT "PA",X,Y,"PD"
6568         IF Pu=1 THEN PRINT "PA",X,Y,"PU"
6572      NEXT Xx
6576      PRINT "PU"
6580  END IF
6584  BEEP
6588  INPUT "WANT TO QUIT (1=Y,0=N(DEFAULT))",Iqt
6592  IF Iqt=1 THEN 6600
6596  GOTO 5916
6600  PRINT "PU PA 0,0 SP0"
6604  SUBEND
6608!
6612!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6616!
6620  SUB Symb(X,Y,Sym,Icl,Hj)
6624  IF Sym>3 THEN PRINT "SM"
6628  IF Sym<4 THEN PRINT "SR 1.4,2.4"
```

```
6632  Yad=0
6636  IF Kj=1 THEN Yad=.8
6640  IF Icl=0 THEN
6644     PRINT "PA",X,Y+Yad,""
6648  ELSE
6652     PRINT "PA",X,Y+Yad,"PD"
6656  END IF
6660  IF Sym>3 THEN PRINT "SP 1.2,1.6"
6664  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
6668  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
6672  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
6676  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
6680  IF Kj=1 THEN PRINT "SM;PR 0,-.8"
6684  SUBEND
6688!
6692!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6696!
6700  SUB Fixup
6704! FILE: FIXUP
6708!
6712  DIM Emf(34),Amp(11),Volt(4),Ldtc(4)
6716  BEEP
6720  INPUT "OLD FILE TO FIXUP",D2file$
6724  ASSIGN @File2 TO D2file$
6728  D1file$="TEST"
6732  CREATE BDAT D1file$,60
6736  ASSIGN @File1 TO D1file$
6740  ENTER @File2;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6744  OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6748  FOR I=1 TO Nrun
6752      ENTER @File2,Told$,Emf(*),Volt(*),Amp(*)
6756      IF I=1 THEN 6764
6760      OUTPUT @File1;Bop,Told$,Emf(*),Volt(*),Amp(*)
6764  NEXT I
6768  ASSIGN @File2 TO *
6772  ASSIGN @File1 TO *
6776! RENAME "TEST" TO D2_file$
6780  BEEP 2000,.2
6784  BEEP 4000,.2
6788  BEEP 4000,.2
6792  SUBEND
6796!
6800!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6804!
6808  SUB Move
6812! FILE NAME: MOVE
6816!
6820  DIM A(66),B(66),C(66),D(66),E(66),F(66),G(66),H(66),J(66),K(66),L(66),M(66
)
6824  DIM N(66),Emf(34),Volt(2),Amp(11),Ldtc(4)
6828  BEEP
6832  INPUT "OLD FILE TO MOVE",D2_file$
6836  ASSIGN @File2 TO D2_file$
6840  ENTER @File2;Nrun,Told$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6844  FOR I=1 TO Nrun
6848      ENTER @File2,Told$
6852      ENTER @File2,A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M(
I),N(I)
6856      ENTER @File2;Emf(*),Volt(*),Amp(*)
6860  NEXT I
```

```
6864  ASSIGN @File2 TO *
6868  BEEP
6872  INPUT "SHIFT DISK AND HIT CONTINUE",Dk
6876  BEEP
6880  INPUT "INPUT BDAT SIZE",Size
6884  CREATE BDAT D2_file$,Size
6888  ASSIGN @File1 TO D2_file$
6892  OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6896  FOR I=1 TO Nrun
6900       OUTPUT @File1;TcId$
6904       OUTPUT @File1,A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M
(I),N(I)
6908       OUTPUT @File1:Emf(*),Volt(*),Amp(*)
6912  NEXT I
6916  ASSIGN @File1 TO *
6920! RENAME "TEST" TO D2_file$
6924  BEEP 2000,.2
6928  BEEP 4000,.2
6932  BEEP 4000,.2
6936  PRINT "DATA FILE MOVED"
6940  SUBEND
6944!
6948!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6952!
6956  SUB Purg
6960  BEEP
6964  INPUT "ENTER FILE NAME TO BE DELETED",Files
6968  PURGE Files
6972  GOTO 6960
6976  SUBEND
6980!
6984!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6988!
6992  SUB Comb
6996! FILE NAME: COMB
7000!
7004  DIM Emf(34),Volt(2),Amp(11),Ldtc(4)
7008  BEEP
7012  INPUT "OLD FILE TO FIXUP",D2_file$
7016  ASSIGN @File2 TO D2_file$
7020  D1_file$="TEST"
7024  CREATE BDAT D1_file$,30
7028  ASSIGN @File1 TO D1_file$
7032  ENTER @File2;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
7036  IF K=0 THEN OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
7040  FOR I=1 TO Nrun
7044  ENTER @File2;Bop,Told$,Emf(*),Volt(*),Amp(*)
7048  OUTPUT @File1;Bop,Told$,Emf(*),Volt(*),Amp(*)
7052  NEXT I
7056  ASSIGN @File2 TO *
7060! RENAME "TEST" TO D2_file$
7064  BEEP 4000,.2
7068  BEEP
7072  Oka=1
7076  INPUT "WANT TO ADD ANOTHER FILE (1=Y,0=N(default))?",Oka
7080  IF Oka=1 THEN
7084  K=1
7088  BEEP
7092  INPUT "GIVE NEW FILE NAME",Nfile$
7096  ASSIGN @File2 TO Nfile$
```

```
7100  GOTO 7032
7104  END IF
7108  ASSIGN @File2 TO *
7112  SUBEND
7116!
7120!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
7124!
7128  SUB Readplot
7132  DIM Qdp(5),Htube(5),Thetab(5)
7136  PRINTER IS 701
7140  INPUT "ENTER FILE NAME",File$
7144  INPUT "ENTER THE NUMBER OF DATA PAIRS",Nrun
7148  ASSIGN @File1 TO File$
7152  FOR I=1 TO Nrun
7156      ENTER @File1;Qdp(*),Htube(*),Thetab(*)
7160      PRINT Qdp(*)
7164      PRINT
7168      PRINT Htube(*)
7172      PRINT
7176      PRINT Thetab(*)
7180      PRINT
7184      PRINT
7188  NEXT I
7192  SUBEND
```

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